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THESIS

FEASIBILITY OF A DYNAMIC DATA RATE SATELLITE LINK FOR INMARSAT

by

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June 2007

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FEASIBILITY OF A DYNAMIC DATA RATE SATELLITE LINK FOR INMARSAT

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ABSTRACT

Inmarsat is a predominantly commercial satellite system fitted on most United States Navy surface vessels including: frigates, cruisers, destroyers, amphibious ships and mine sweepers. It is primarily used for telephone, fax, email, web browsing, and the Global Command and Control System (GCCS). Inmarsat, however, has a very limited data rate. For ships fitted with the latest modem upgrade, Inmarsat provides a meager 128 kbps for support of its numerous functions. To improve upon Inmarsat's limited data rate, this thesis suggests a potential improvement to Inmarsat communications by integrating a dynamic data rate link that maintains the required probability of bit error without exceeding the allocated bandwidth. The results from this thesis show that link margin provisions from the static data rate design are able to support much greater data rates using advanced modulation and forward error correction techniques. The proposed adaptive dynamic link improves the link by measuring channel conditions to determine the fastest data rate for successful communications. When channel conditions are good, the adaptive dynamic link will communicate at a high data rate, and when channel conditions are poor, the dynamic link will communicate at a lower data rate to maintain a target probability of bit error ceiling.

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EXECUTIVE SUMMARY

Technological advances have transformed the battlefield and combat effectiveness has become, more than ever, highly contingent upon maintaining the information advantage through the dissemination and acquisition of information at greater speeds and volumes. The need for increased speed and volume of information required for combat effectiveness has developed due to numerous factors. Military engagements that used to take days are now measured in seconds. Survivability of forces requires the dispersion of units while at the same time units must communicate to draw combat power from each other through sea based and aircraft fire support. The Navy's continual shift from classroom training to Navy Knowledge Online (NKO) web based training, the development of local and global sensors that must be continually shared in order for joint forces to obtain a common operational picture, and the development of high endurance unmanned platforms for sea, air, and space operation that require significant amounts of data rate all contribute to the overloading of the limited capacity of many currently established communication links. To truly deliver FORCEnet's objective of network-centric warfare, the available bandwidth of communication links must be efficiently utilized for the maximum exchange of information that is vital to the cooperative success of U.S. military forces. Conventional communications links provide a margin of bandwidth to ensure connectivity at the expense of a lower data rate of communication. The proposed dynamic data rate system presented in this thesis increases the data rate of communication by optimizing the use of the available bandwidth by measuring channel conditions and then varying the data rate accordingly to the maximum data rate that the channel can support. When measured channel conditions are poor, a low data rate of communication is established to guarantee connectivity and when channel conditions are good, a higher data rate of communication is

established. The proposed systems periodic measurement of varying channel condition ensures communication at the maximum data rate without the use of conventional link margins.

I. THESIS INTRODUCTION

A. OBJECTIVE

Inmarsat is a private company that operates a constellation of geostationary satellites primarily for maritime phone and data communications. The main objective of this thesis is to improve Inmarsat's capacity for U.S. Navy maritime data communications by investigating the feasibility of integrating a dynamic data rate feature into U.S. Navy communications via Inmarsat satellites.

B. RELEVANCE

As the U.S. Navy's operational tempo continues to increase, the demand for higher data rate communications also continues to grow. Inmarsat is the primary data communications link for the majority of surface vessels in the U.S. Navy fleet [1]. These vessels include frigates, cruisers, destroyers, mine sweepers, and smaller amphibious ships. Without Inmarsat, these ships that are regularly being deployed on extended deployments and surged for the numerous operational requirements would have no means for telephone, email and web browsing, all of which are necessary for operational information exchange between ships and shore facilities. Aside from operational requirements, Inmarsat is invaluable to sailors that depend on Inmarsat for communication with their family through email. Although Inmarsat is able to provide the services mentioned above, it provides the services very poorly, only allowing data rate transfers to and from the ship at a meager 128 kbps. To put this into perspective, consider a crew of 240-330 people sharing two 56 kbps dial up modems for all their family emails, combined with all the messages and web browsing required for shipboard operations.

To satisfy the growing needs of the U.S. Navy for higher data rate communications for ship to ship and ship to shore communications, it is essential to make efficient use of the available bandwidth and signal power. To maximize the data rate through the Inmarsat channel, a dynamic data rate satellite link is

proposed. The current Inmarsat system operates at a static data rate, and by the very nature of static data rate systems underutilizes the link. This is because, although the signal-to-noise ratio (SNR) varies depending upon a variety of factors such as weather, electromagnetic interference (EMI), and propagation distance, a static data rate system operates at a fixed data rate regardless of the varying signal power available to the system. This fixed data rate is chosen by design so as to close the link at the worst conceivable SNR and is incapable of using the channel's increased capacity when the SNR increases above this worst-case value. The proposed dynamic satellite system, takes advantage of varying signal power by increasing the data rate for channel conditions where SNR is good and decreasing the data rate for channel conditions where SNR is poor. By doing so, the specified probability of bit error is maintained, and the use of the bandwidth and signal power is optimized for varying channel conditions.

C.   ORGANIZATION

This thesis is arranged into five chapters with specific objectives. Chapter II provides the reader with a brief background of Inmarsat. In this chapter, the history of Inmarsat is discussed. It gives the reasons why Inmarsat was established and describes the organization as it is today. This chapter also discusses the interoperation and integration of Inmarsat equipment with the other communications equipment on U.S. Navy ships to provide the services offered by Inmarsat. Furthermore, the chapter provides specifications regarding Inmarsat that allows engineers to analyze the system. Chapter III analyzes Inmarsat using the specifications discussed in Chapter II. In this chapter, it is determined that Inmarsat's allocated bandwidth and available signal power are able to support data rates greater than that of the current system. Chapter IV discusses the challenges faced in implementing a dynamic data rate satellite link. It discusses the methods of how the data rate can be varied in a communications system and explains why one method is preferred over the other. This chapter also discusses the methods of measuring the channel's integrity and why one method is most preferred. Moreover, this chapter provides a system model of successful

demodulation of a dynamic satellite link. Chapter V discusses the conclusion and findings in this thesis. It also provides recommendations for future work.

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II. THE INMARSAT SYSTEM

A. CHAPTER INTRODUCTION

Naval operations inherently require warships to be at great distances from each other and from shore activities that support their mission. This vast separation of ships from their resources and command elements makes communications essential for the successful execution of naval combat operations. Due to the need for fast and efficient communications for modern military operations, the Navy has been quick to adopt satellite communication to bridge the communications barrier intrinsic in naval operations. Among the many satellite systems available, one of the systems most widely used by the Navy is the Inmarsat satellite system because of its rapid and reliable connections and broad coverage. Inmarsat, however, has a significant limitation in its data rate capacity, which prompts its investigation in this thesis [1].

In this chapter, the system study of Inmarsat begins with a brief overview of the early history of Inmarsat and a brief overview of its current organization. This chapter includes a basic understanding of the current Inmarsat system, its main components and how they interoperate to make available the services it offers to the U.S. Navy. Other key objectives in this chapter are to provide specifications for the main components of Inmarsat that would enable a meaningful analysis of the system and to determine whether the main components of Inmarsat are able to support higher data rates than are currently supported.

B. HISTORY AND EARLY ORGANIZATION

In 1972, the escalating congestion and interference within the available maritime frequencies prompted the Intergovernmental Maritime Organization (IMO) to conduct a series of studies to initiate the development of a reliable satellite system that would provide high quality voice and data communications between commercial ships and the public communications network. Of primary

concern for the envisioned system was the handling of distress and safety messages and the locating of maritime vessels in distress. After the initial studies were conducted, the IMO convened in 1975 to discuss the implementation of the envisioned system. Based upon the unanimous agreement of the 48 representatives of the different member nations, the International Maritime Satellite Organization (Inmarsat) was established to administer the implementation and operation of the system. [2]

It was not until 1979 that Inmarsat began full operation and provided improved reliability for distress and safety messages and improved communications for the efficient management of ships and maritime correspondence. Due to Inmarsat's success, it later extended its services to provide for land and aeronautical communications. At its early beginnings, Inmarsat was composed of 26 member nations; by mid 1995 its membership had grown to 79 member nations. The investment share of each member nation was based upon the volume of communications to and from the member nation's registered ships and the total tonnage of ships registered with each member nation. Inmarsat was organized with an assembly consisting of representatives from each member nation that met every two years to discuss and plan the management and long term goals of the organization. To resolve issues regarding policy and management within the organization, each member of the assembly had one vote. Inmarsat's organization also consisted of a council that met three times a year. The council was composed of the representatives of the 18 largest share holders and 4 representatives for the collective group of smaller share holders. The council advised the Directorate, who was responsible for the daily management of the organization. Unlike the assembly, the council's voting was weighted according to the investment percentages of the member nations. [2]

C.   INMARSAT TODAY

In 1999, Inmarsat became a private company that operates a constellation of geostationary satellites for phone, facsimile exchange (Fax), teleprinter exchange (Telex), and data communications around the world. The satellites are managed from Inmarsat's headquarters in London and are comprised of four third generation satellites (Inmarsat-III) as the primary satellites and back-up satellites consisting of one third generation satellite and four second generation satellites (Inmarsat-II). Since its inception as a private company, Inmarsat has ventured into a range of business opportunities in information technology and land and cellular telephony, but still remains to provide communication services for the traditional maritime market. The Inmarsat system of today is used by a vast array of customers requiring voice and data communications services. Current users include the U.S. military, foreign militaries, ship owners and managers, journalists and broadcasters, health and disaster-relief workers, land transport fleet operators, airlines, airline passengers, air traffic controllers, national emergency and civil defense agencies, and many others. [3]

The current Inmarsat system can be broken down into four parts. First is the Mobile Earth Station (MES) or Ship Earth Station (SES). MESs and SESs are the actual user terminals that subscribe to the services offered by Inmarsat. The SES operates in the L-band (1 to 2 GHz) with a frequency allocation depending upon the type of service. The second part of the system are the geostationary satellites positioned above the Pacific, Indian and Atlantic Oceans. Figure 1 shows the four geostationary satellites approximately 35,700 km above the earth positioned at 15.5°W and 54°W (Atlantic Ocean Region), 64.5°E (Indian Ocean Region) and 178°E (Pacific Ocean Region). Figure 2 illustrates that the combined coverage of the four satellites spans all the major oceans and the majority of the globe. The current satellites in service are the Inmarsat II (back-up) and Inmarsat III (primary and back-up) that operate in both the C-band and the L-band. Inmarsat IV, the next generation of Inmarsat satellites, have been recently launched and are scheduled to be in service in the near future. The third

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part of the system consists of four Network Coordination Stations (NCS), one for each satellite, which coordinate the transmission and reception of signals between mobile and land based stations. The last component of the Inmarsat system is the Land-Earth Station (LES). The LES routes calls to or from a mobile earth station via the satellite for connection to the national and international phone and data networks. Conversely, the LES routes calls from the international and phone data networks to or from mobile earth stations. The frequencies used for communication between the satellite and LES are in the C-band (4 to 8 GHz). [4, 5]

The current Inmarsat system is available in a variety of configurations. The Inmarsat-A system is the original SES Inmarsat system that was derived from an older system called the COMSAT MARISAT system. It provides subscribers telephone and fax services between the Public Switched Telephone Network (PSTN) and properly equipped ships. In April 1990, Inmarsat-A had 10,500 subscribers, 88% of which were large ships. This system consisted of relatively large components and at the time cost approximately $50,000 each. Using the first generation satellites, the Inmarsat-A system was limited to 60 simultaneous telephone channels per satellite due to the satellite's low capacity. With the advent of digital satellite techniques for voice, data coding, and modulation, the analog Inmarsat-A system has become obsolete and the Inmarsat-B system was developed as its digital equivalent. [7]
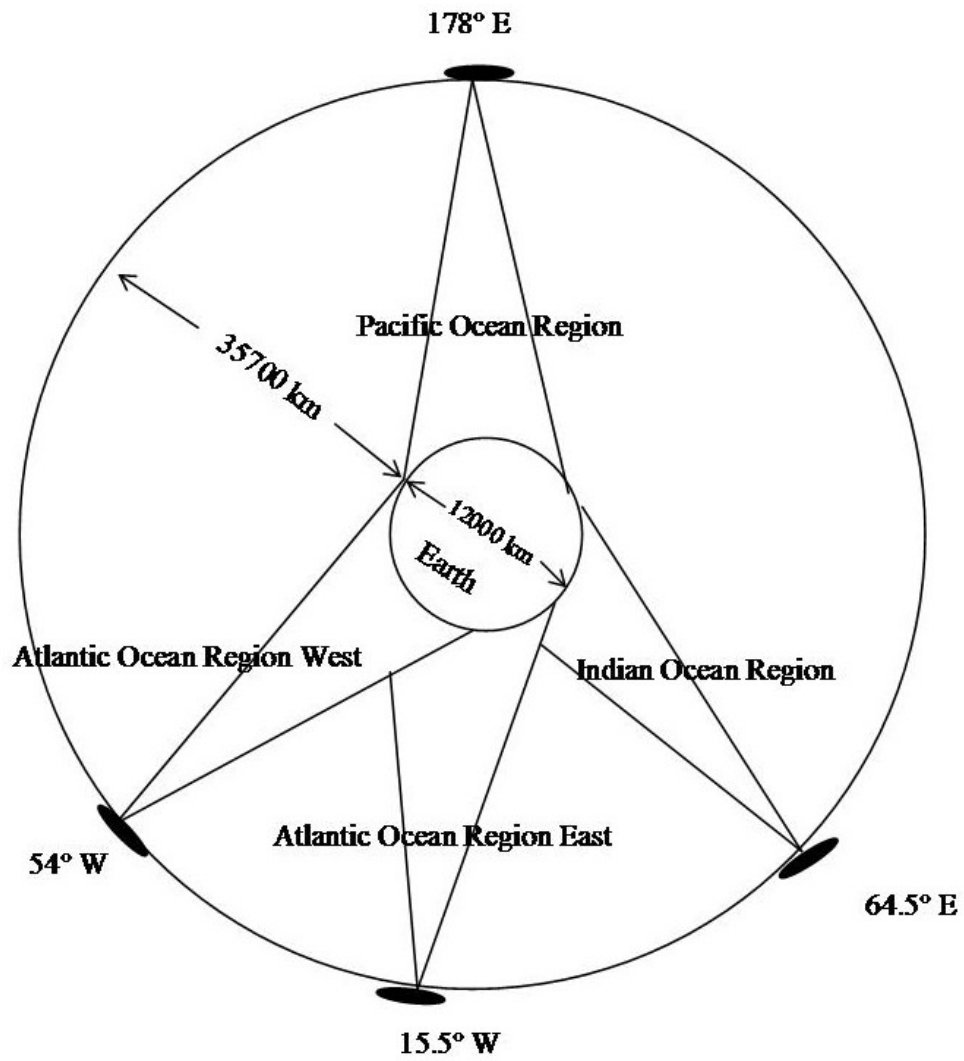
Figure 1.   Inmarsat Geostationary Satellites (After [5])
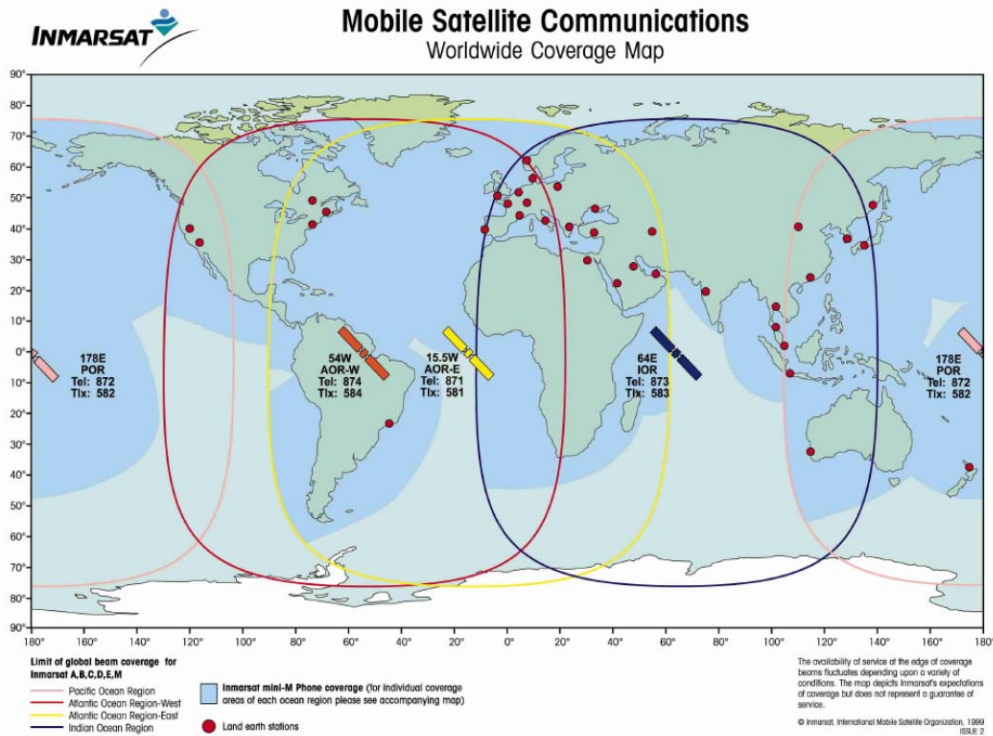
Figure 2.   Inmarsat Coverage Map (From [6])

The Inmarsat-B terminal, together with the third generation of satellites (Inmarsat-III), is able to support more channels simultaneously because of up to seven spot beams that allow a relatively small geographic area to reuse all the available channels in the system. The concept behind spot beams is similar to that of cellular phones. By allowing an antenna radiation pattern to encompass only a small geographic area, all channels are available for use in a small geographic area without interfering with adjacent areas covered by a different spot beam. The increased capacity due to the spot beams used in Inmarsat-B comes at the price of increased protocol complexity. In addition to the phone and fax services offered by the Inmarsat-A system, low-speed asynchronous data (300 bps) and medium-speed (9.6 kbps) data services are supported. Inmarsat-B, however, offers comparably much higher data rates with a high speed data (HSD) service capable of 64 kbps. [7]

Inmarsat-B and Ultra High Frequency (UHF) are the most common satellite links used for communication throughout the U.S. Navy fleet. Ships not equipped with the higher performance systems such as the Defense Satellite Communications System (DSCS) and Challenge Athena III are mainly the smaller ships such as frigates (FFG), cruisers (CG), destroyers (DDG), oilers (AOE), and small amphibious ships (LPD and LSD) [8]. Because the majority of the U.S. Navy fleet is comprised of vessels fitted with Inmarsat-B and UHF, Inmarsat-B and UHF are undoubtedly the most common communications links used by the U.S. Navy fleet. For these smaller vessels, Inmarsat-B is their best option for communications because it provides relatively higher data rates, providing 100 kHz for each channel as to compared to UHF that provides only 25 kHz channels [1]. Single terminal Inmarsat systems can provide 32 kbps of voice and 32 kbps of data. Some ships have two Inmarsat-B systems installed and typically have 32 kbps for voice and 96 kbps for data [8]. Inmarsat-B uses a relatively small antenna (1 meter diameter parabolic antenna) which is one of the primary reasons why it is so well suited for small vessels [5]. U.S. Navy ships lease their own 100 kHz satellite channels for point-to-point communication with the Inmarsat LES. The U.S. Navy leases 120 channels at $24,000 per channel per month [8]. Formerly, the LESs used by the Navy were located in Fucino, Italy, Perth, Australia and Southbury, Connecticut. Due to the Navy's renewed contract with Inmarsat, the current LESs used for Navy applications are located in Auckland, New Zealand, Goodhilly, United Kingdom, and Laurentides, Canada. The LESs are each connected to a Naval Computer and Telecommunications Area Master Station (NCTAMS) via a T-1 line which can be configured to carry voice or data traffic [8, 9]. Figure 3 shows the configuration of the Navy shore infrastructure for satellite and terrestrial communications.

A new external modem capable of a data rate of 128 kbps has been developed and installed in U.S. Navy ships [10]. Further information on the external modem will be discussed in the following sub-topic.
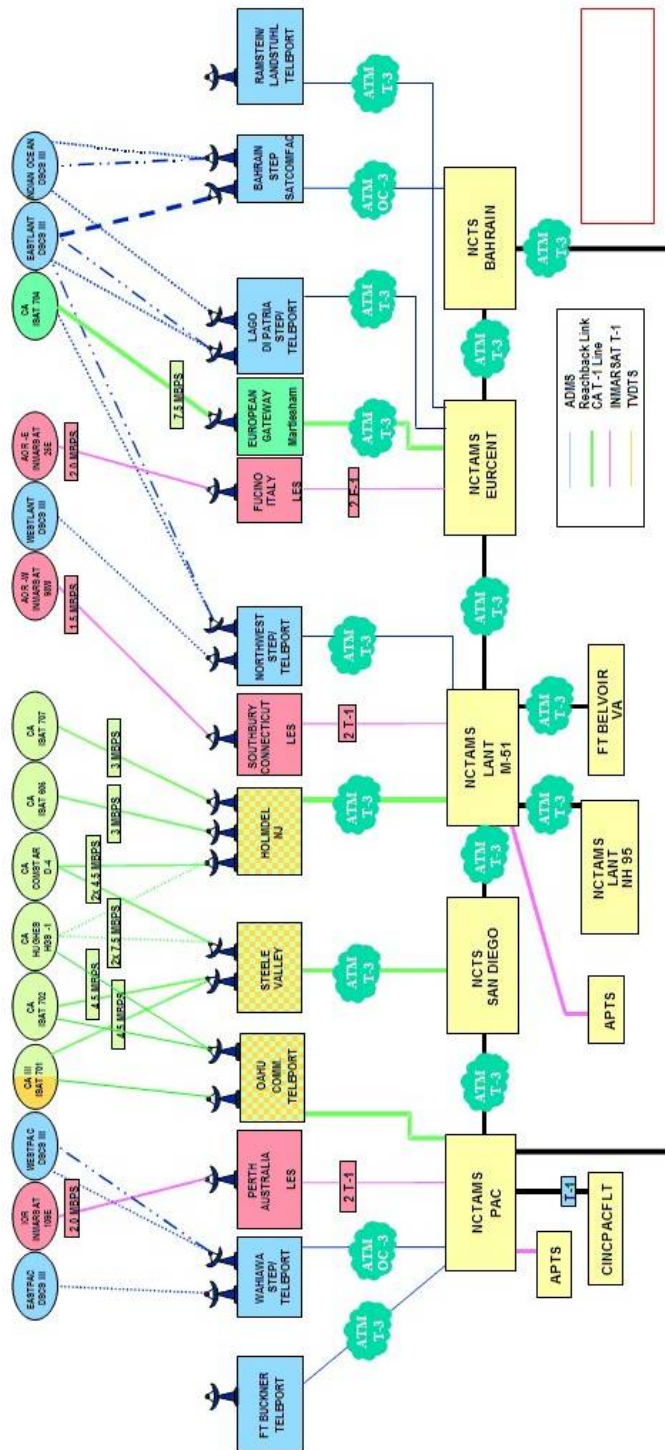
Figure 3.   U.S. Navy Communications Infrastructure (From [9])

D.   BASIC INMARSAT SYSTEM

The basic Inmarsat system is shown in Figure 4. Communication can either be initiated by the SES or the land based telephone network, fax network, or data network connected to an LES. Each satellite region is under the control of a Network Coordination Station (NCS).
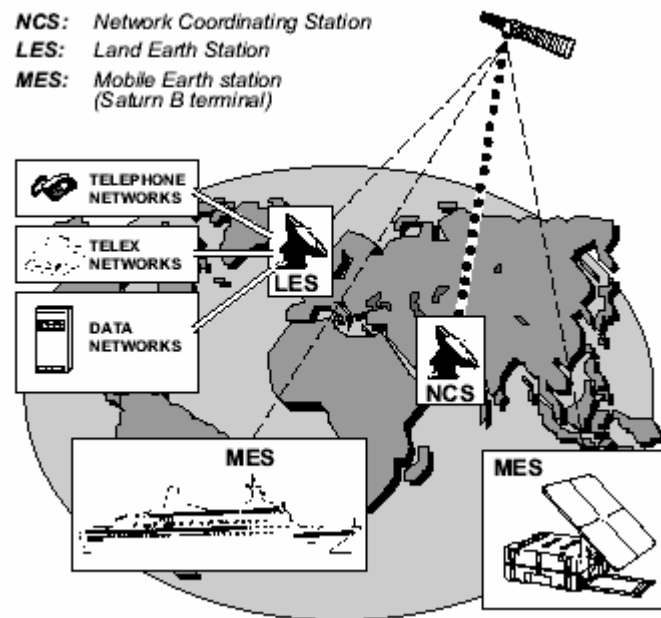
Figure 4.   Basic Inmarsat System (From [5])

The NCS manages the traffic between the SES and LES. The NCS in each ocean region continually transmits a signal via satellite to all the SESs within its region on the NCS Common Signaling Channel (NCSC). To establish a communications link, the SES automatically configures its receiver to the NCSC and transmits a signal requesting a channel assignment together with information that identifies itself. The NCS checks the System Information Bulletin Board, which contains all the available NCS/LES channel frequencies, location of satellites, operational status, etc. After the NCS locates an available channel, it sends a Call Announcement via satellite to the SES and LES detailing the channel to which the SES and LES should tune to for transmission and reception

of information. After the channel is assigned by the NCS, the LES takes over control of the channel from the NCS, after which the SES and LES/SES are free to communicate via satellite. [5]

E.   INMARSAT TERMINAL AND ASSOCIATED SHIPBOARD COMPONENTS

Commercial applications of Inmarsat simply require that a ship is fitted with a specific terminal, called the Saturn Bm, designed for satellite communication via Inmarsat. Military applications, however, require other aspects such as encryption, data routing, and multiplexing that commercial Inmarsat terminals do not provide. To satisfy the tactical needs of the U.S. Navy, other shipboard components are integrated with the Inmarsat terminal. These shipboard components tailor the commercial Inmarsat system to satisfy operational requirements of the U.S. Navy [8]. They include the Automated Digital Network System (ADNS), KG-84A, and AN/FCC-100. A typical ship network topology taken from the USS OKANE (DDG-77) is illustrated in Figure 5, which shows how the various shipboard components interoperate with the Saturn Bm [11].

To transmit digital information (digital bit stream) via Inmarsat, all information from data networks is first routed to the ADNS router [8]. The ADNS routes the digital information to two KG-84As that encrypt the information for security. The first encryption device (KG-84A #1) receives the bit stream at 64 kbps. After encrypting the bit stream it sends the encrypted information to the Saturn Bm modem at 64 kbps [9]. The Saturn Bm converts the encrypted digital information to symbols using quadrature phase-shift keying (QPSK) modulation and a rate 1/2 forward error correction (FEC) code and transmits in the L-band. Using QPSK modulation, the Saturn Bm modem is able to transmit two bits per symbol, where a symbol is a waveform mapped into a constellation diagram (more on this later). To send the digital information at 64 kbps together with the rate 1/2 FEC, the modem transmits at 64 ksps (kilo symbols per second) [4].

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Thus, the modem is sending a total of 128 kbps, 64 kbps of which is data and 64 kbps of which is the coding necessary to achieve a specified bit error probability.
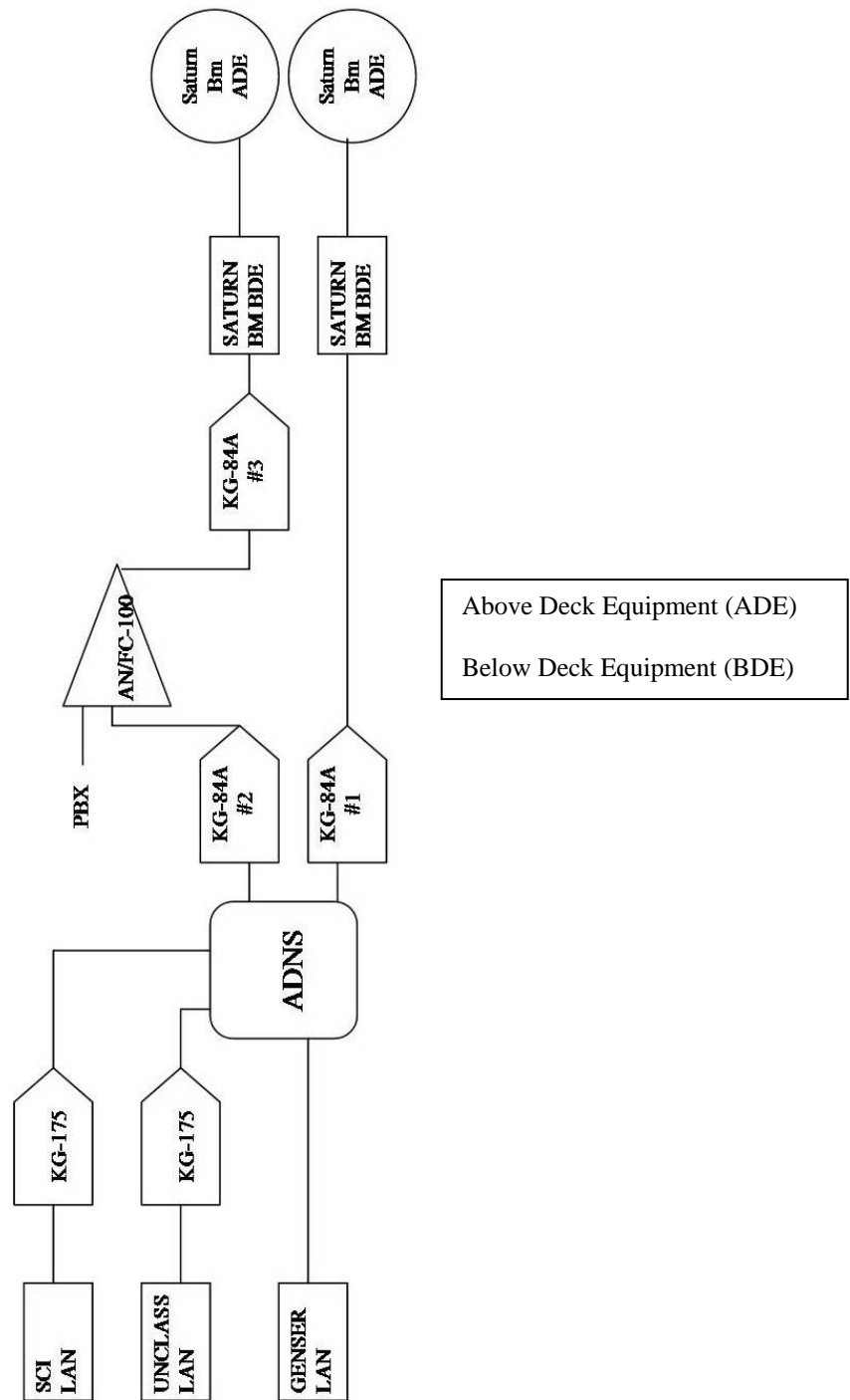
Figure 5.   Typical SES Network Topology (After [11])

The second encryption device (KG-84A #2) receives digital information from the ADNS at a rate of 32 kbps [8]. After encrypting, the KG-84A #2 sends the encrypted data to the AN/FCC-100. The AN/FCC-100 is a multiplexer, which multiplexes a 32 kbps digital voice bit stream from the Public Branch Exchange (PBX), a telephone switch, together with the digital data from the ADNS. The aggregate output from the AN/FCC-100 is 64 kbps of multiplexed voice and data bit streams. The AN/FCC-100 sends its aggregate output to another KG-84A (KG-84A #3) for transmission security of the digital voice information [11]. The KG-84A (KG-84 #3) sends the encrypted voice and data bit streams to the second Saturn Bm terminal. The Saturn Bm handles the 64 kbps bit stream exactly the same way as the Saturn Bm terminal discussed earlier. However, at the second Saturn Bm terminal, 32 kbps of voice information is transmitted and received and 32 kbps of data is transmitted and received. Thus, a particular ship with two Saturn Bm terminals is able to transmit data at 96 kbps and transmit digital voice information at 32 kbps. To receive voice and data, the process is the reverse of transmission. [8, 11]

Due to the severe limitation in the data rate of the current Inmarsat modem, recently an external modem developed by Comtech Systems, Inc. has been connected to the Saturn Bm terminal on a select number of ships so as to increase the data rate of each Saturn Bm terminal to 128 kbps. Figure 6 is a simplified diagram showing the configuration of the external modem and Saturn Bm. Note that the external modem is interconnected to the ADNS through a KG-84A, similar to what is shown in Figure 5. [10]

As previously mentioned, the Inmarsat-based shipboard system is composed of five main parts: ADNS, encryption devices, multiplexer, Saturn Bm terminal, and external modem. The preceeding discussion explained the basic interaction of the shipboard components. In the following discussion, the components are described further with some of their specifications and capabilities.

1. Automated Digital Network System (ADNS)

The ADNS is the backbone of a ship's communications system. Through the ADNS Internet Protocol router, digital data is automatically routed from secret, unclassified, and Sensitive Compartmented Information (SCI) Local Area Networks (LANs) via Inmarsat, Defense Satellite Communications System (DSCS), or other communications satellites. The ADNS concept is well illustrated in Figure 7.   The figure depicts the ADNS ability to allow a single access point for all network inputs instead of the former multiple fixed parallel paths architecture. The ADNS hardware is illustrated in Figure 8.   [8]
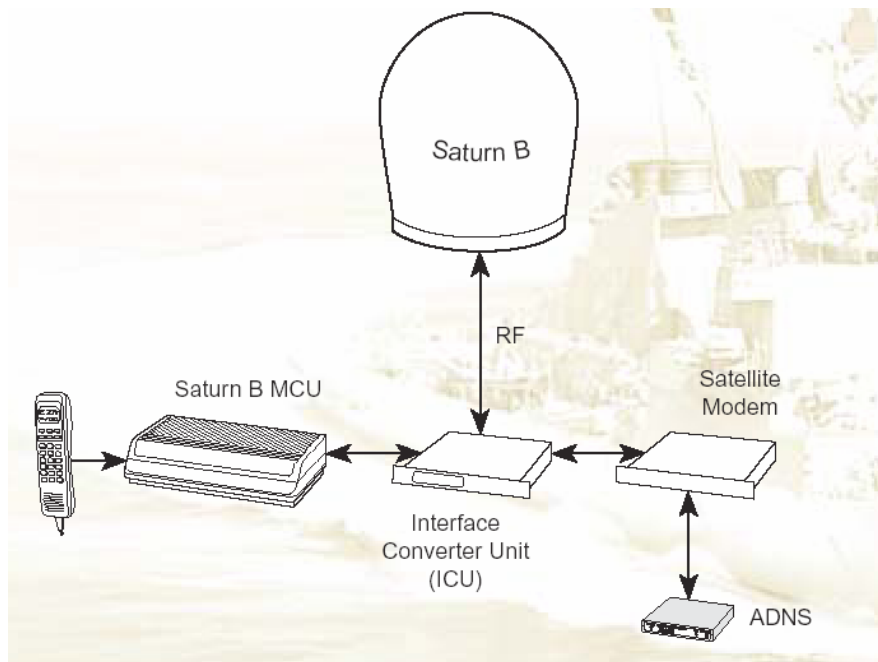
Figure 6.   Saturn Bm External Comtech Modem System (From [10])
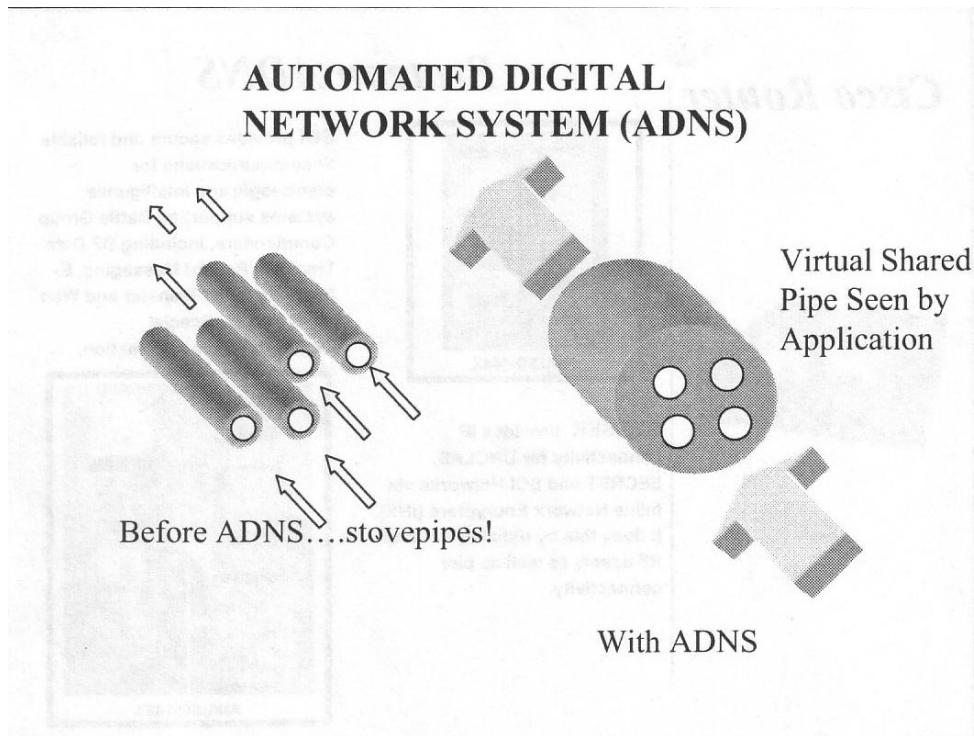
Figure 7.   ADNS Concept (From [8])

Figure 8.   ADNS AN/USQ-144V (From [8])

2.   KG-84A

The KG-84A, shown in Figure 9, is a general purpose crypto device used
to encrypt and decrypt digital information for secured links. It is certified for all
levels of security and can be used with a variety of other devices and modems.
As shown in Figure 10, a KG-84A typically serves as the interfacing element
between the input/output (I/O) device and the modem that is either connected to
the communications channel or connected to another crypto device. The KG-84A
can also be connected to another KG-84A for further processing before

connection to the I/O device.   The KG-84A is normally operated in full duplex but can also be operated in half duplex and simplex modes. [12]

Figure 9.   KG-84A (From [15])
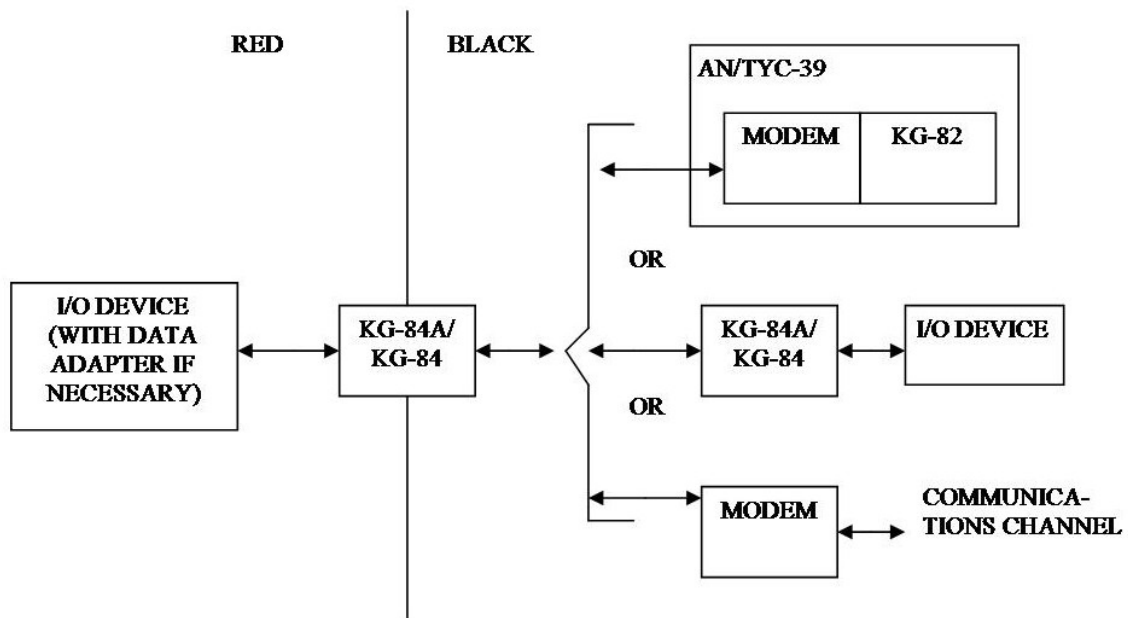
Figure 10.   Typical KG-84A Interface (From [12])

The unit can be operated in either synchronous or asynchronous modes. Synchronous data transmission is a form of transmission wherein bits of digital information are grouped together in equal sized blocks and are sent through the channel at regular time intervals. To successfully demodulate each block of bits, both the transmitter and receiver must be in synchronization with each other in order to determine where each block begins and ends. To accomplish synchronization, special bits called synchronization bits are sent before the transmission of actual data. These synchronization bits inform the transmitter and receiver of the proper timing interval of the transmission of blocks. On the other hand, asynchronous transmission is a form of transmission wherein bits of digital information are grouped together in a block of varying length by means of start and stop bits. Start bits are sent to inform the receiver that a block of bits is about to be sent through the channel, and stop bits are sent to inform the receiver that the block of bits has completed transmission. The KG-84A allows synchronous data rates up to 256 kbps and asynchronous data rates of up to 96 Mbps [13]. The decrypted message is sent to a compatible I/O device. For Inmarsat, the KG-84A sends the decrypted bit stream to the ADNS for routing or to the AN/FCC-100 for demultiplexing. A binary word called a crypto key stored in the unit is used for the encryption and decryption of digital bit streams. To successfully transfer digital information, both the sending and the receiving KG-84A within the communications link must use identical crypto keys. [12]

Another feature of the KG-84A is that it can perform continuous automatic synchronization in high quality traffic channels [12]. At bit error probabilities greater than 10^{-5}, the KG-84A will lose synchronization [14]. Additional details regarding the KG-84A can be found in [12].

3. AN/FCC-100

The AN/FCC-100, shown in Figure 11, is a voice and data multiplexer commonly used for military and other secure applications. By definition, a

multiplexer receives a variable number of inputs (called the interface) from different sources and combines the inputs to form one output (called the aggregate).

Figure 11.　　AN/FCC-100 (From [16])

The AN/FCC-100 can support up to 16 inputs at data rates of up to 64 kbps each. Its aggregate output provides for full duplex and simplex communication with independent transmission and reception rates. For U.S. Navy applications, the AN/FCC-100's aggregate is commonly configured for synchronous operation. Using synchronous interfaces, the AN/FCC-100 is capable of supporting crypto resynchronization for circuits that require the encryption of large amounts of data. For satellite applications, the AN/FCC-100 has a user defined satellite aggregate buffer for offsetting the timing variations related with the day to day variations in the satellite signal. Such timing variations can be caused by the varying propagation distance of the satellite to the mobile terminal. In Chapter III, the maximum propagation distance was calculated to be approximately 41033 km. The typical minimum propagation distance for geostationary satellites was approximately 35700 km. Frome these distances, the speed of light (2.998×10^8

m/s), and the data rate (64 kbps) together with the velocity equation $(v = d / t)$, the timing difference caused by the time it takes for light to travel the minimum and maximum propagation distances is calculated to be [16]

$$\left(\frac{41033km - 35700km}{2.998 \text{x} 10^8 m / s} \cdot \frac{1000m}{1km} \cdot 64000 \ bits / s \right) = 1138 \ bits \qquad (2.1)$$

The AN/FCC-100 comes in different versions. Version 4 is what is commonly installed in current U.S. Navy vessels, such as the USS O'KANE (DDG-77) [11]. Version 9 is the latest version available and can be expected to be used for future upgrades in the U.S. Navy because of its greater capabilities, such as being able to support greater data rates over a single aggregate. In the synchronous mode, version 9 is capable of supporting data rates of 768 kbps. The AN/FCC-100 is capable of configuration for a variety of applications. If desired, the AN/FCC-100 can multiplex SIPRnet (Secret) and NIPRnet (Unclassified) traffic over a single aggregate. However, such a configuration entails the use of two routers, which may be undesirable. The possible configuration for the AN/FCC-100 discussed above is shown in Figure 12. [16]
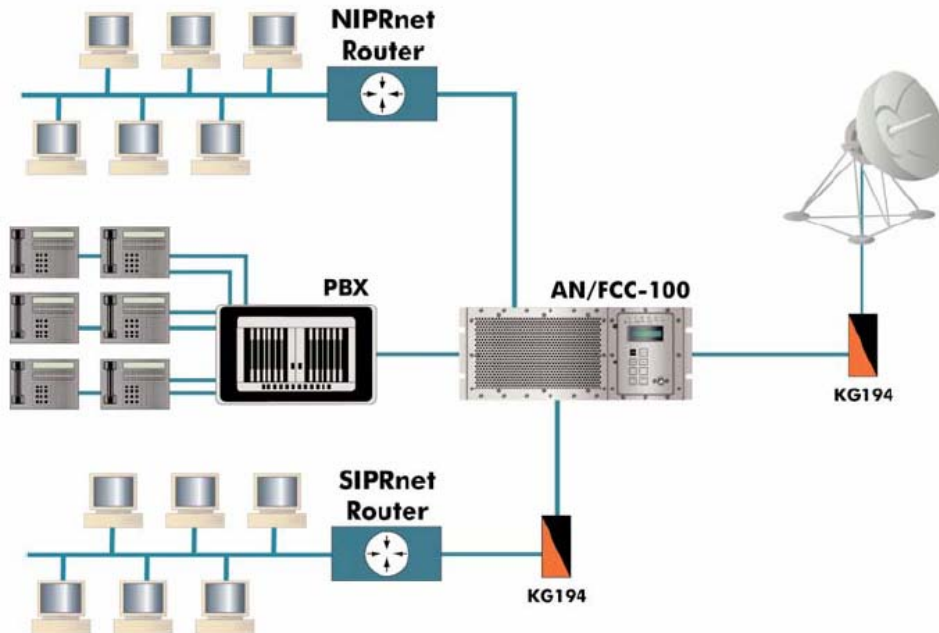
Figure 12.   AN/FCC-100's Possible Configuration (From [16])

4. Saturn Bm

The Saturn Bm is characterized by two main components, the Above Deck Equipment (ADE) and the Below Deck Equipment (BDE). As their names imply the ADE is located on the ship's upper level, and the BDE is located in one of the ship's internal compartments, typically in the radio room. For frigates, however, the BDE is located in a compartment under the flight deck. The ADE and BDE work together to receive and transmit digital information via satellite.

a. *Below Deck Equipment (BDE)*

The BDE is more commonly referred to as the modem. Its main function is to map digital information into a constellation diagram of waveforms that each symbolizes a bit or a group of bits. The constellation diagram depends upon the type of modulation. The BDE uses two types of modulation, binary phase-shift keying (BPSK) for communication between the SES/LES and NCS and quadrature phase-shift keying (QPSK) for communication between the SES and LES [[2]]. A typical constellation diagram for QPSK is shown in Figure 13. The constellation diagram is a visual tool that represents the different waveforms, commonly called symbols, which correspond to a bit or a group of bits. The signal waveforms are represented in the constellation diagram by vectors in a polar plot. The length of the vector corresponds to the signal amplitude, and the vector direction corresponds to the signal phase. At the transmitter of a QPSK modem, bits being transmitted are first grouped into pairs.
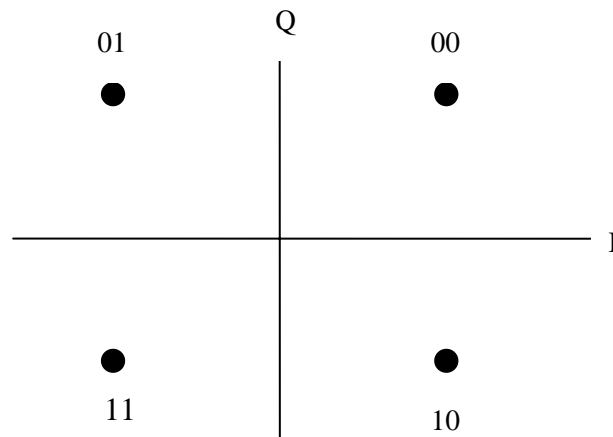
Figure 13.   QPSK Constellation Diagram

Then the modulator produces one of four waveforms for each pair (00, 01, 10, or 11) of bits to be transmitted. At the receiving modem, the received waveform is translated according to the constellation diagram. If the received waveform has a phase between 0 and 90 degrees, the waveform is interpreted as bits 00. A waveform with a phase between 90 and 180 degrees is interpreted as bits 01. The two other groups of bits (11, 10) are represented by the remaining symbol waveforms with phases between 180 and 270 degrees and between 270 and 360 degrees, respectively. Notice from Figure 13 that adjacent symbols differ by only one bit. This method of assigning bits to symbols is called *gray coding.* Gray coding is often employed in symbol assignments because it minimizes the number of bit errors. For example, if the intended group of bits being transmitted is 00 and the noise from the receiver distorts the waveform so that the receiving modem interprets the waveform as the adjacent waveform representing bits 01 or 10, there would be an error of only one bit. If the symbols were assigned differently such that adjacent symbols differ by two bits, then noise would cause more errors than when gray coding is employed. [17]

b.   *Above Deck Equipment (ADE)*

The ADE shown in Figures 15 and 15 is a parabolic dish antenna that transmits and receives radio signals to and from the satellite. To transmit

and receive radio signals successfully, the ADE is equipped with various sensors and motors that allow the ADE to remain stable with respect to the satellite despite the constant changes in the pitch, roll, and bearing of the ship. The ADE is connected to a gyro assembly inside the ship, which gathers information relating to the pitch and roll of the ship. The ADE is equipped with an ACU (Antenna Control Unit) that gathers information from antenna position sensors and gyro assembly for controlling the electric motors that keep the antenna pointed towards the satellite. One other important component of the ADE is the RF unit. The RF unit interfaces the received and transmitted RF signals to the modem, and serves the important function of amplifying received and transmitted signals. [5]

Figure 14.   Above Deck Equipment
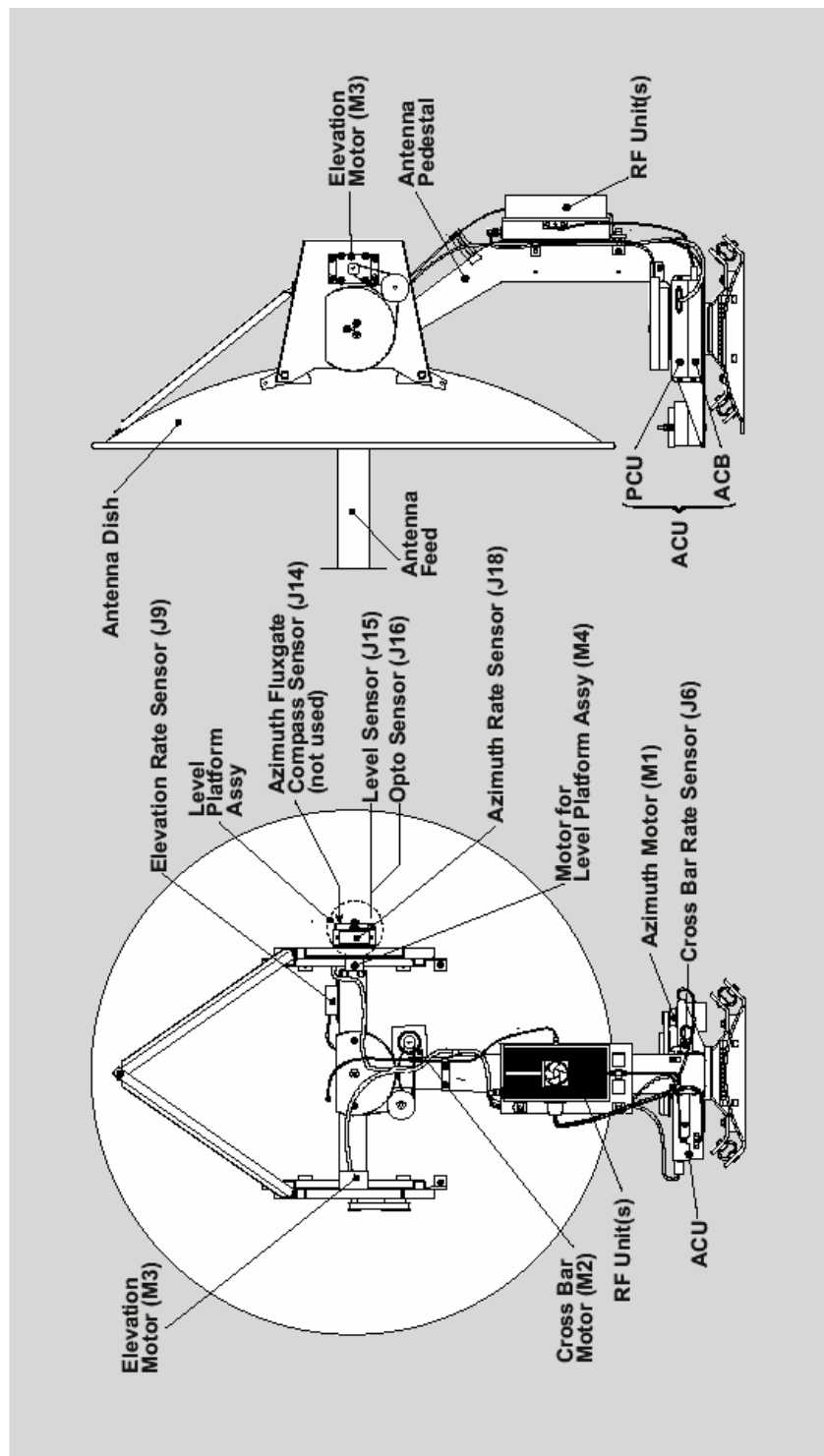
Figure 15.　　　Above Deck Equipment (From [5])

c. Saturn Bm Technical Data

Tables 1-5 give the technical data for the Saturn Bm. These tables contain the following information: services available, system specifications, physical characteristics, environmental conditions, and power requirements.

Table 1.   Services (After [5]]

Voice	16 kbps
Fax	9.6 kbps
Telex (Teleprinter Exchange)	50 Baud
Asynchronous Data	9.6 kbps
High Speed Data	56/64 kbps full duplex

Table 2.   System Specifications (After [5, 18)

Transmit Frequencies	1626.5 – 1646.5 MHz
EIRP	33 dBW
Receive Frequencies	1530.0 – 1559.0 MHz
Bandwidth	100 kHz (HSD)
G/T	-4 dB/K

Table 3.   Antenna Unit (After [5])

Diameter	1 m (parabolic dish)
Gain	21.8 dB Tx, 21.1 dB Rx
Polarization	Right-hand circular
Steerability	Hemispheric coverage, 0-90 deg.
Tracking	Automatic search
Ship Motion	
Max turning rate	12°/sec
Roll	±30°
Pitch	±10°
Yaw	±8°

Table 4.   Environmental Conditions (After [5])

Above Deck Equipment	
Temperature	-25°C to 55°C
Rain	100 mm/hour
Below Deck Equipment	
Temperature	-25°C to 55°C
Humidity	95 % at 40°C

Table 5.   Power Requirements (After [5])

Voltage	11-34 VDC
Power Consumption	150 W
Power Supply	220 VAC to 28 VDC
Back Up Power Supply	24 VDC

5. External Comtech Modem System

The U.S. Navy has recently undertaken measures to improve upon the 64 kbps data rate of Inmarsat by integrating an external modem made by Comtech EF Data Corporation to increase Inmarsat's data rate to 128 kbps. The external modem functions primarily the same as the Saturn Bm except that it uses a more advanced coding and modulation scheme that allows it to be capable of a significantly greater data rate while still using the same 100 kHz leased bandwidth. Because the external modem is a more advanced and capable modem, digital data that was formerly processed by the Saturn Bm is instead routed to the external modem for processing. In the external modem configuration, the Saturn Bm only serves the function of controlling the parabolic antenna for alignment with the satellite. The Saturn Bm and the external modem are connected to each other through an Interface Conversion Unit (ICU) that functions as a frequency converter unit, converting the external modem's 70 MHz Intermediate Frequency (IF) to the Saturn Bm's ADE L-band signal and vice versa. [10]

F. INMARSAT SATELLITE

Due to the increasing number of ships that subscribe to Inmarsat services and aeronautical subscribers that require high power due to their small antennas, the capacity of Inmarsat-II satellites have been significantly exceeded. To satisfy the need for greater capacity, higher capacity Inmarsat-III satellites have been developed to replace the Inmarsat-II satellites well before their operational lifetime had expired. Inmarsat-II satellites now only serve as back-up satellites. The enhanced capacity of the Inmarsat-III satellites is due to their capability to use up to seven ocean sized spot beams in the L-band transmit and receive frequencies which allow the reuse of all the available channels. Anywhere from four to seven spot beams are used to cover the global beam's footprint for L-band communication between the SES and the satellite. Furthermore, the spot beams are reconfigurable, which allow the satellite to provide spot beam

coverage at any location within the satellite's global footprint. The Inmarsat-III satellite is also capable of adapting to variable traffic loads by allocating its total L-band power among the spot beams and the global beam. Reference [2] enumerates the payload of Inmarsat-III:

- C-band to L-band forward channel for communications from fixed terminals (LES).
- L-band to C-band return channels for communications from mobile terminals.
- C-band to C-band channel for administrative traffic between fixed terminals.
- L-band to L-band channel for direct traffic between mobile terminals.
- Navigation channel

The main parts of the satellite payload are the C-band to L-band channel and the L-band to C-band channel, which are primarily used for ship to/from shore communications. For search and rescue, the global beam L-band to L-band channel is used. The navigation channel is used to supplement the U.S. Global Positioning System and the Russian Glonass System [2]. Additional details for Inmarsat-III (F-5) are outlined in Table 6. Table 7 outlines the characteristics of an Inmarsat LES. [2]

The Inmarsat III satellite was designed with spot beams that have coverage areas small enough to take advantage of frequency reuse and large enough to mitigate the payload complexity that increases with the number of coverage areas. The spot beams are for L-band transmission and reception, and the global beam is for C-band transmission and reception. The Inmarsat III satellite's 22 solid state power amplifiers combined with a beam forming matrix allows power to be routed to any one beam or distributed among many beams, both global and spot beams. The nominal equivalent isotropic radiated power ($EIRP$) distribution for the global beam is 39 dBW and 44 dBW for the spot beams. [2, 19]

The Inmarsat satellite is a nonregenerative repeater; that is, it only amplifies and retransmits the received waveforms without any demodulation or reconstitution.

Table 6.   Inmarsat-III F5 (After [2, 5, 19])

Inclination	±2.7°
Coverage	Global and Spot
Launch Date	February 4, 1998
Typical Uses	Maritime, Aero, and Land Mobile
Type of Satellite	GE Astro Series 4000
Stabilization	3-axis
Prime Contractors	Lockheed Martin Astro Space
Launch Weight	2,000 kg
Mass in Orbit	860 kg
Design Lifetime	13 years
Dimensions	2 x 7 x 20 ft
Electric Power	2,800 Watts
SSPA Power	C-Band: 1 @ 15 Watts; L-Band: 1@440 Watts
Transmit Frequencies	3600 to 3629 MHz (C to C), 1525 to 1529 MHz and 1530 to 1559 (L to L, C to L), 1574.4 to 1576.6 MHz (Nav)
Receiver Frequencies	1626.5 – 1646.5 MHz (L to C), 6425 to 6454 MHz (C to C), 6454.4 to 6456.6 MHz (Nav)
Number of Transponders	C-Band: 1; L-Band: 1
Channel Polarization	C-Band: (LHCP&RHCP transmit & receive; L-Band: (RHCP)
EIRP	L-Band: Global 39 dBW, Spot 44 dBW; C-Band: 27.5 dBW
G/T	L-Band: Global Beam: -6.5 dB/K; Spot Beams: -2.5 dB/K

Table 7.   Inmarsat Land Earth Station Characteristics (After [2])

Parameter	Land Earth Station
Transmit Band	C
Receive Band	C
Transmit EIRP, dBW	≤70
Receive G/T, dB/K	≥32
Antenna Type	Parabolic Reflector
Typical Antenna Size	32 to 42 ft diameter
Typical Gain, dBi	48 to 56

A common feature in nonregenerative satellites is the dependence of the downlink power to the uplink power, where the downlink power is shared in proportion to the number and power of uplink signals plus noise. Thus, if mobile stations have equal uplink transmission power levels, each mobile station has an equal amount of downlink power. The downlink power allocated to each user is equal to the satellite's total downlink $EIRP$ divided by the number of users (mobile stations) communicating through the satellite. If a mobile station increases its uplink transmission power level, this enhances its downlink signal power in proportion to its uplink power increase at the expense of degrading the downlink signal levels of all other users. To avoid this disproportionate distribution of the satellite's total $EIRP$, all users must cooperate with one another and not exceed the established uplink transmission power level. [2, 17]

G.   SUMMARY AND CONCLUSION

In this chapter, the history and early organization of Inmarsat, together with its current organization, were briefly presented. It was revealed that Inmarsat is a robust satellite system that provides improved communications for maritime applications. Among the desirable attributes of Inmarsat are its global coverage and its rapid and reliable connections. Inmarsat, however, was shown to be limited in its data rate capacity, providing only 64 kbps using its Saturn Bm terminal and 128 kbps using an integrated external modem. Although the data rate has greatly improved, the 128 kbps data rate that the external modem provides is unable to cope with the growing needs of the U.S. Navy for modern

combat operations. Applications such as target acquisition, electronic support, intelligence gathering, and command and control require increased data rates. To further improve upon the data rate for Inmarsat-equipped Navy ships, this thesis seeks to optimize the allocated 100 kHz bandwidth by incorporating a dynamic link that measures the channel quality and uses this measure to optimize the data rate for the channel. This goal was motivated by the conjecture that the current use of the allocated bandwidth is not optimized due to the link margin applied in the link budget of the current design.

A valuable finding from the investigation of the Inmarsat system in this chapter was that the main shipboard components integrated with Inmarsat are able to support higher data rates than that of the current data rate. This finding demonstrates that if a means is found to increase Inmarsat's data rate, the shipboard components other than the modem will not need to be replaced, making a modification to the existing system more economically desirable than a totally new system design. In the next chapter, the Inmarsat specifications gathered in this chapter are used to analyze the current system and show that the allocated bandwidth is underutilized and that the implementation of a dynamic data rate link is feasible with Inmarsat.

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III.   INMARSAT ANALYSIS

A.   CHAPTER INTRODUCTION

In the previous chapter, a brief overview of Inmarsat was presented. It was shown how the components of Inmarsat are integrated to make available the Inmarsat services. Furthermore, a description of the ship earth station, Inmarsat satellite and Inmarsat shipboard component capabilities were given together with a listing of their system specifications. In this chapter, the information gathered in Chapter II is used to analyze the current Inmarsat system installed onboard U.S. Navy ships.

The goal of this thesis is to determine the technical feasibility of a dynamic data rate link over Inmarsat. To determine Inmarsat's potential for a dynamic link, it is essential to first determine whether the allocated bandwidth and available power in the system is able to support data rates greater than the current 128 kbps. In this chapter, it is shown that Inmarsat's ship-to-shore link and shore-to-ship link are underutilized and that the available power and bandwidth can support much higher data rates through advanced modulation and coding techniques. The analysis begins with a link budget.

B.   LINK BUDGET

Conventionally, the first step in designing a satellite system is the performance of a satellite link budget. A link budget is simply the addition and subtraction of gains and losses in a radio link. When the gains and losses of various system components are summed together with the losses, the result is an estimation of the system performance in the real world. To arrive at an accurate answer, every factor than contributes to gain or loss must be included. These factors include, but are not limited to, atmospheric losses through distance, transmit and receive antenna gains, input/output transponder back-off, cable losses, and satellite and ground receiver system temperature. In link budget calculations for digital communications, the parameter of greatest interest

is the ratio of the received signal power to the noise power spectral density. This parameter is of great significance to a link budget because it is a measure of the quality of the link. The link budget begins with the link budget equation given by

$$\frac{P_r}{N_o} = EIRP + \frac{G}{T} - BO - LOSSES - k_B \qquad (3.1)$$

where P_r / N_o is the ratio of received signal power to noise power spectral density, expressed in units of dBHz, $EIRP$ is the equivalent isotropic radiated power, expressed in units of dBW, G/T is the ratio of the receiver antenna gain to the system temperature, expressed in units of dB/K, BO is the input/output back-off, expressed in units of dB, $LOSSES$ is the total link loss, also expressed in units of dB and k_B is Boltzmann's constant, which has a value of -228.60 dBW/(HzK) [20].

The parameters $EIRP$ and G/T for Inmarsat are available from Table 6 and Table 7. Although the total link loss generally includes additional losses other than free space loss such as rain attenuation, antenna misalignment loss, and polarization mismatch loss, for this thesis only free space loss is accounted for. This is because a typical static data rate satellite link is designed based upon a link budget for the worst case signal power so that the system will be able to maintain a link under the worst conceivable circumstances. For the envisioned design, as the losses change due to various factors, the data rate will automatically change to maintain an optimized link. Thus, the proposed system design should not be based upon the worst case specifications but on the highest sustainable data rate. This corresponds to the best conditions. The highest sustainable data rate can be determined through a link budget that includes no losses except for free space loss. The free space loss is given by

$$FSL = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 \qquad (3.2)$$

where d is the distance between the transmitting and the receiving antennas and λ is the wavelength of the signal [20]. To calculate d, the geometry shown in Figure 16 and Figure 17 is considered. Figure 16 shows the geometry of the

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satellite with respect to the earth. Figure 17 shows the earth with relevant points, angles, and arcs (labeled at top of figure) and the triangle formed by the satellite, the earth station, and the center of the earth (bottom of figure).   The variables denoted in Figures 16 and 17 are as follows:
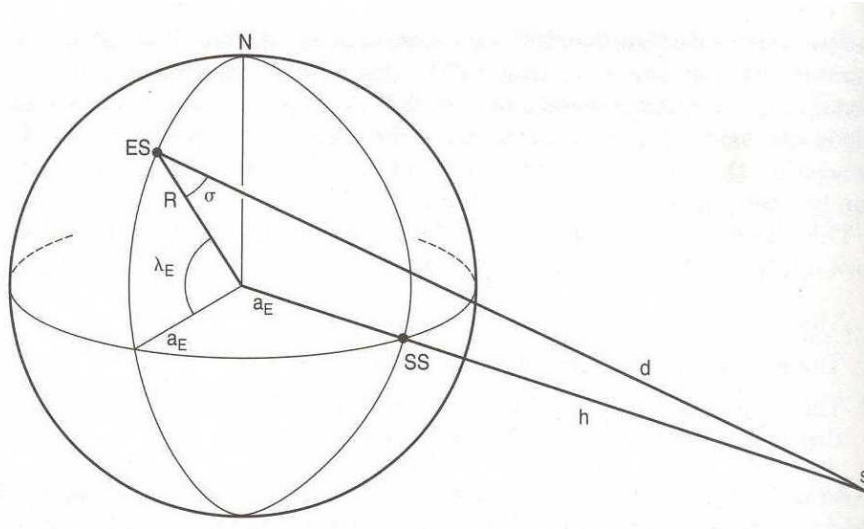
Figure 16.   Satellite and Earth Geometry (From [20])
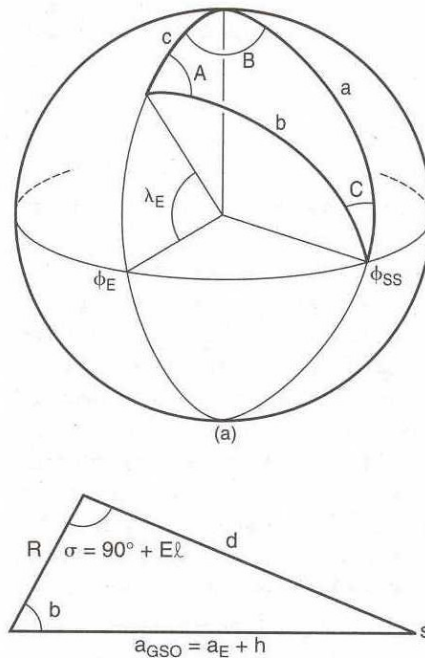
Figure 17.   Spherical and Plane Geometry of Figure 16 (From [20])

S	- the geostationary satellite
SS	- the sub-satellite point (the point on the earth's equator directly below the satellite)
ES	- the (land or ship) earth station
a_E, R	- the radius of the earth
h	- the altitude of the satellite over the sub-satellite point
d	- the range of the satellite (i.e. the distance between the earth station and the satellite)
N	- the north pole
λ_E	- the latitude of the earth station (north latitudes taken as positive values, south latitudes taken as negative values)
a, b, c	- the central angles (angles opposite the corresponding arcs whose vertices are at the center of the earth)
A, B, C	- the surface angles (angle between arcs) of the spherical triangle
	Note: A spherical triangle is a three sided figure where each side is an arc of a great circle. A great circle is a circle on the surface of a sphere and centered on the center of the sphere (in this case on the surface of the earth and centered on the center of the earth).
ϕ_E	- the longitude of the earth station (west longitudes taken as negative values, east longitudes as positive values)
ϕ_{SS}	- the longitude of the sub-satellite point

$E\ell$ - the elevation angle (the angle measured in the local vertical plane between the satellite and the local horizon)

σ - the elevation angle plus 90°

a_{GSO} - the distance between a geostationary satellite and the center of the earth (42,164 km). [20]

For the spherical triangle in Figure 17,

$$a = 90° \tag{3.3}$$
$$B = \phi_E - \phi_{SS} \tag{3.4}$$
$$c = 90° - \lambda_E . \tag{3.5}$$

Note than when the earth station is east of the subsatellite point, B is positive and when west of the subsatellite point, B is negative. Also note that c is less than 90° when the earth station is in the northern hemisphere and greater than 90° when the earth station is in the southern hemisphere [20]. From the law of cosines for angles, angle b is [21]

$$\cos(b) = \cos(a)\cos(c) + \sin(a)\sin(c)\cos(B) . \tag{3.6}$$

Combining Equations 3.3 through 3.6, we obtain

$$b = \cos^{-1}\left[\cos(90)\cos(90 - \lambda_E) + \sin(90)\sin(90 - \lambda_E)\cos(\phi_E - \phi_{SS})\right] . \tag{3.7}$$

Equation 3.7 can be further simplified as

$$b = \cos^{-1}\left[\cos(\lambda_E)\cos(\phi_E - \phi_{SS})\right] . \tag{3.8}$$

Applying the law of cosines for sides to the plane triangle in Figure 17 allows the range d to be found to a close approximation:

$$d = \sqrt{R^2 + a_{GSO}^2 - 2Ra_{GSO}\cos b} . \tag{3.9}$$

The law of sines can also be applied to the plane triangle in Figure 17 to find the angle of elevation of the antenna. A low angle of elevation means that the antenna is pointed towards the horizon; in practical systems, 5° is typically the minimum angle of elevation. The maximum angle of elevation is 90°, which means that the antenna is pointed straight up. The angle of elevation is contingent upon the location of the earth terminal with respect to the satellite. At

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the edge of the satellite's global beam footprint, the antenna has a low angle of elevation. When the earth station is at the sub-satellite point, the antenna has a 90° elevation. The angle of elevation is [20]

$$El = \cos^{-1}\left(\frac{a_{GSO}}{d}\sin b\right).$$ (3.10)

1.   Inmarsat's Free Space Loss

Before continuing with the link budget analysis, it is helpful to first investigate how the position of the ship earth station with respect to the satellite affects the amount of free space loss in the system. Note again that a ship earth station located at the edge of the satellite footprint has a low angle of elevation and, thus, is farther from the satellite than an earth station located in the middle of the satellite's footprint. To investigate the effects of varying the distance of the ship earth station from the satellite, the satellite Inmarsat-III F4 which is located at 54° West longitude, is used. For illustration purposes, let the ship earth station be located at the coast of Whidbey Island, Washington, latitude 48° North and longitude 122° West. Referring back to the Inmarsat coverage map (Figure 2), we notice that the coast of Washington state is just at the edge of the beam coverage of Inmarsat-III F4. First, the distance between the satellite and ship earth station is calculated. Using Equation 3.8 and the latitude and longitude given above, we obtain

$$b = \cos^{-1}[\cos(48)\cos(122-54)] = 75.4834°.$$ (3.11)

The value for b calculated above is used to calculate the range d. From Equation 3.9, d is calculated as 41033 km, where R =6371 km and a_{GSO} =42164 km [20]. From Equation 3.10, the angle of elevation (El) is 5.869˚. The value for d above is also used to determine the free space loss. From Equation 3.2, the free space loss is 188.955 dB, where 1630.5 MHz is the frequency used by the ship to transmit to the satellite and where $\lambda = c/f$ [20]. Next, the free space loss of an earth station located at the sub-satellite point is calculated using Equation 3.2, where d =35700 km, and the free space loss is 187.746 dB.

The results from the calculations above reveal an interesting fact about Inmarsat. Although the distance from the satellite to the edge of the footprint is greater than the distance from the satellite to the sub-satellite point by roughly 5333 km, the free space loss of a ship located at the edge of the satellite's footprint differs by approximately 1.2 dB from the free space loss of a ship located at the sub-satellite point. This shows that a ship located at the sub-satellite point is capable of communicating at a higher data rate than that of a ship located at the edge of the satellite's footprint due to performance degradation from free space loss.

2. Inmarsat Link Budget

The link budget for Inmarsat can be readily calculated from Equation 3.1, Equation 3.2, and the specifications listed in Tables 2, 6 and 7. Because Inmarsat transmits and receives radio signals on different frequencies, for the calculations that follow, the lowest frequencies that Inmarsat uses for transmission and reception are used. In doing so, the results will give the ideal value of P_r/N_o. Use of the specifications from Inmarsat-II result in lower P_r/N_o values. The link budget for Inmarsat is tabulated in Tables 8, 9, 10 and 11.

Table 8.   Ship to Satellite (After [5, 19])

Quantity	
Ship Station $EIRP$	33.00 dBW
Free Space Loss @ 1626.5MHz	187.73 dB
Satellite G/T	-6.5 dB/K
$-k$ (Boltzmann's Constant)	228.60 dBW/(HzK)
Uplink P_r/N_o	**67.37 dBHz**

Table 9.   Satellite to Land Earth Station (After [2, 19])

Quantity	
Satellite $EIRP$	39 dBW
Free Space Loss @ 3600 MHz	194.63 dB
LES G/T	32.00 dB/K
$-k$ (Boltzmann's Constant)	228.60 dBW/(HzK)
Downlink P_r/N_o	**104.97 dBHz**

Table 10.   Land Earth Station to Satellite (After [[2, 19])

Quantity	
LES $EIRP$	70 dBW
Free Space Loss @ 6425 MHz	199.69 dB
Satellite G/T	-6.5 dB/K
$-k$ (Boltzmann's Constant)	228.60 dBW/(HzK)
Uplink P_r/N_o	**92.44 dBHz**

Table 11.   Satellite (Spot Beam) to Ship Earth Station (After [5, 19])

Quantity	
Satellite Mobile Channel $EIRP$ (Spot Beam)	44 dBW
Free Space Loss @1525 MHz	187.19 dB
Ship G/T	-4 dB/K
$-k$ (Boltzmann's Constant)	228.60 dBW/(HzK)
Downlink P_r/N_o	**81.41 dBHz**

Observe that the input/output back-off parameter common for satellites with traveling wave tube amplifiers (TWTA) is not accounted for in the link budget. This is because Inmarsat III satellites are installed with solid state power amplifiers (SSPA) and not TWTAs [2]. Also observe that the ship-to-satellite link has the lowest value (67.37 dB) of P_r/N_o; this indicates that the ship-to-satellite link is the weakest part of the communications link and is most susceptible to noise and interference. This is not the typical situation in most satellite systems. A typical satellite system is limited by the power of the satellite's transponders. It is suspected that the ship-to-satellite link is the weakest link because the Inmarsat-B system was designed before the Inmarsat-III satellites were launched. The first Inmarsat-III satellite was launched April 4, 1996, while the Inmarsat-B terminals were developed in the 1980's [7, 19]. After Inmarsat upgraded to the more powerful Inmarsat-III satellites, the Inmarsat-B system installed in naval vessels may not have been upgraded so as to allow the satellite to support a greater number of users. Recall from the discussion of nonregenerative repeaters in Chapter II that the mobile link L-band $EIRP$ is dependent not only on the number of users but also upon the transmit power of each user plus noise. Increasing the ship-to-satellite $EIRP$ of each user

increases the allocated satellite-to-ship spot beam $EIRP$ for all users at the expense decreasing the number of L-band users that the satellite can support. This is because the satellite's total L-band spot beam $EIRP$ is distributed into larger portions. Thus, from the link budget shown above, a significant increase in data rate can be achieved by upgrading the ship earth station transmitters but at the expense of decreasing the number of users that the satellite can support. Furthermore, the link budget reveals the links between the satellite and LES are very robust and are not as susceptible to the effects of channel degradation when compared to the ship-to-satellite and satellite-to-ship links which have lower P_r / N_o values. This is an import discovery because it reveals that the channel between the SES and the satellite is the limiting factor affecting the overall performance of the duplex link. Thus, for the implementation of a dynamic link, only the channel between the satellite and the ship needs to be monitored in order to determine the maximum data rate allowable through the channel. [17]

It is unclear whether the spot beam $EIRP$ values indicated in references [2] and [19] are the mobile link $EIRP$ or the satellite's total L-band $EIRP$. The conclusions from the above discussion are based upon the assumption that the spot beam $EIRP$ indicated in [2] and [19] is the mobile link $EIRP$. This assumption is supported in Appendix A. In the next subsection, the maximum data rate that can be supported by the upstream and downstream P_r / N_o through the available bandwidth is investigated.

C.   SHANNON CAPACITY

The next step in the analysis of Inmarsat is to determine the maximum data rate that the available bandwidth and power can sustain. Studies by C. E. Shannon showed that the system capacity of an additive white Gaussian noise (AWGN) channel is a function of the signal-to-noise ratio (SNR) and the bandwidth W [17]. The capacity relationship, known as the Shannon limit, is [17]

$$C = W \log_2(1 + SNR) \tag{3.12}$$

where

$$SNR = \frac{P_r}{N_o W} .$$ (3.13)

From the limiting P_r / N_o calculated in the link budget (67.37 dBHz for the ship-to-satellite link) and 100 KHz for W, which is the bandwidth allocated for Inmarsat high speed data (HSD) transfers, the SNR is calculated using Equation 3.13 and is 54.576 [22].The capacity of the channel (C) is calculated using Equation 3.12 and is 579 kbps.

The calculated value for C reveals that the maximum data rate that can be supported by the available bandwidth and power for upstream links is 579 kbps. The Shannon limit, however, is not generally attainable in practical systems. It does indicate that through the application of advanced modulation and coding techniques the maximum data rate achievable in Inmarsat is much greater than its current 128 kbps data rate. Consider that even if only half the data rate specified in the Shannon limit is attained, the upstream link performance improvement through Inmarsat will still be very significant.

The calculations above only reveal the maximum data rate at which the ship is able to transmit. Next, the maximum data rate at which the ship is able to receive from the satellite is determined. Following the procedures for the calculations above and substituting the P_r / N_o value for the satellite-to-ship link via the spot beam (Table 11) into Equation 3.13, we calculate the SNR to be 1383.57, and the capacity through the downstream link is 1.043 Mbps. The result from the calculation above reveals that there is a disparity by a factor of 1.8 between Inmarsat's maximum data rate capacity for upstream and downstream links. It also further shows that the bandwidth and signal power are under-utilized by the static design, providing only a data rate of 128 kbps in both forward and reverse directions.

D. MODULATION

Inmarsat is both power and bandwidth limited. To achieve higher data rates, a bandwidth and power efficient modulation technique is essential. Among the different modulation schemes available, it is important to choose a modulation scheme that will give the highest data rate possible with the least amount of signal power for the given bandwidth. Before a modulation scheme can be chosen, it is essential to understand the measures of performance for any type of modulation. There are two closely related measures of the performance of a modulation scheme, the probability of symbol error and the probability of bit error. Probability of symbol error is the probability that the waveform sent by the transmitter is interpreted by the receiving modem to be a symbol other than the one sent. When a symbol error occurs, the bit or group of bits that the symbol represents are lost due to the receiver's misidentification of the symbol. It is easy to see that symbol errors are directly proportional to the number of received bit errors. The probability of receiving bits in error is defined as the probability of bit error, also commonly called bit error ratio. [17]

To properly choose the most efficient modulation scheme, it is helpful to use Figure 18. Figure 18 shows the most popular modulation schemes and their spectral efficiency R/W (bit per second per hertz of bandwidth) versus the SNR per bit (E_b/N_o) required to achieve a bit error probability of 10^{-5}. In Figure 18, the variable M is defined as $M = 2^k$ where k is the number of bits per symbol. For M-ary quadrature amplitude modulation (MQAM) and M-ary phase-shift keying (MPSK) observe that increasing M results in a higher spectral efficiency R/W. The increase in R/W signifies an increase in the amount of information bits transferred per unit of bandwidth. This increase in data rate, however, comes at the cost of increased SNR required to achieve a specific bit error ratio [23]
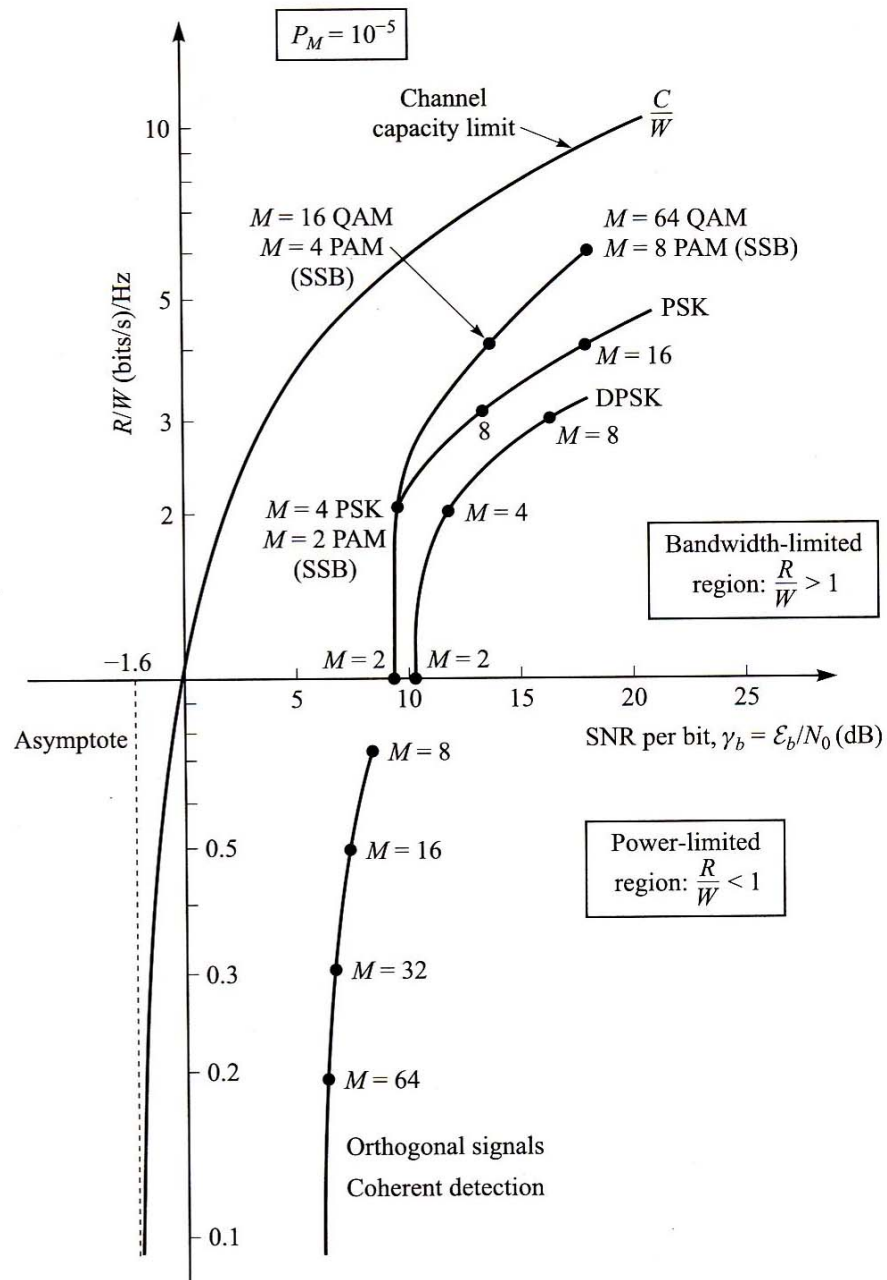
Figure 18.   Comparison of Common Modulation Schemes (From [23])

Among the modulation techniques shown, as M increases, MQAM requires the least amount of SNR per bit. Specifically, 16-QAM requires less SNR than 16-PSK. Moreover, as M increases, MQAM approaches the Shannon capacity more quickly than other types of modulation. Because it is apparent from Figure 18 that MQAM yields the greatest throughput with the least amount of power, it will be the modulation scheme of choice for the proposed Inmarsat link. Notice that by merely changing the modulation scheme from QPSK to the more efficient MQAM, a higher system data rate can be achieved. [23]

Figure 18 also shows that in situations where power is limited it is desirable to implement M-ary orthogonal modulation. Observe that for M-ary orthogonal signals, when M is increased the required SNR decreases. However, such a modulation scheme is only practical for cases where there is a large amount of bandwidth available. Although orthogonal signal modulation is power efficient, it requires an excessive amount of bandwidth. Thus, orthogonal signal modulation is impractical for Inmarsat and for any communication system where bandwidth is at a premium. [23]

MQAM is a modulation scheme where the symbol waveforms bear information through both their magnitude and phase. A typical constellation diagram for MQAM used in the IEEE 802.11 standard is shown in Figure 19. Recall that a constellation diagram represents a modulation

scheme with the length of the vector representing the amplitude and the vector direction representing the phase. Notice that, unlike MPSK, discussed in Chapter II, the constellation diagram for MQAM does not have a constant amplitude but rather a varying amplitude and phase. In the particular example in Figure 19, a symbol waveform carries four bits of information. To minimize bit errors, gray coding is employed. [23]

It should be noted that MQAM has a disadvantage since it does not have a constant amplitude and, therefore, does not have constant power. If the transmitter utilizes a traveling wave tube amplifier (TWTA) or other non-linear

amplifier, the power transmitted out of the amplifier must, in general, be reduced, or "backed off", so that the transmitter does not distort the signal, corrupting the amplitude information. Often this reduction in transmit power is sufficient to substantially reduce link capacity. In this thesis, the author did not investigate this issue. It is presumed that if this issue impacts the modulations proposed herein for Inmarsat in a substantial way, that other modulations could be used. For example, continuous phase modulation, including Gaussian minimum shift-keying, are constant power and, while not as bandwidth efficient as MQAM, they are reasonably bandwidth efficient. [18]

Now that a modulation scheme has been chosen, the next step in the analysis is to determine the maximum data rate that can be achieved using MQAM. The probability of symbol error, denoted by P_S, is shown in [23] to be upper bounded by

$$P_S \leq 4Q\left(\sqrt{\frac{3kE_b}{(M-1)N_o}} \right) \tag{3.14}$$

where $k \geq 1$ and E_b / N_o is the average SNR.

From the specifications listed in Chapter II, the maximum data rate that the KG-84A can support is 256 kbps [12]. Any data rate greater than this means that more capable cryptologic equipment must be installed in ship terminals. The question is: can Inmarsat's available bandwidth and power sustain a data rate of 256 kbps using MQAM? Inmarsat's current data rate of 128 kbps with a FEC code rate of ¾ implies a coded data rate of 171 kbps [5]. In this case, one code bit is added for every three bits of data. Thus, for a data rate of 128 kbps using QPSK modulation, a coded data rate of 171 kbps is transmitted. To transmit 171 kbps using QPSK, a symbol rate of 86 ksps is necessary [17].
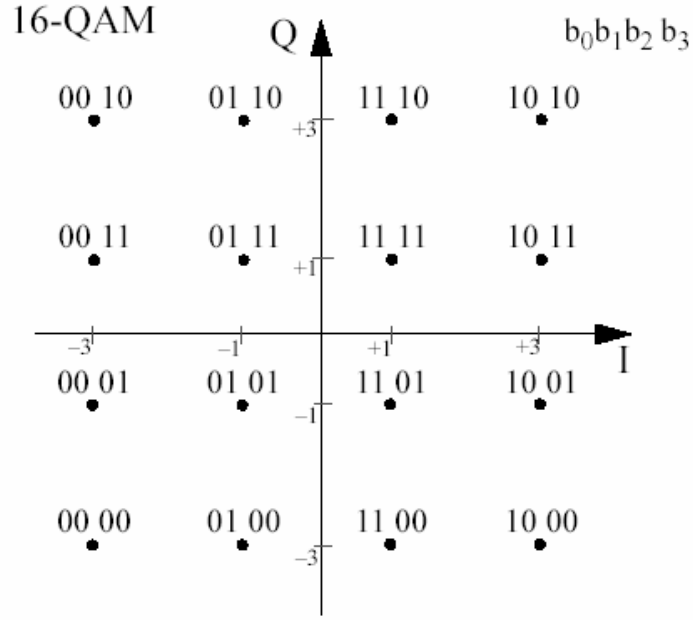
Figure 19.   16 QAM Constellation Diagram (From [24])

To achieve a data rate of 256 kbps, each symbol needs to carry at least three bits of information. To transmit three bits of information per symbol, 8-QAM is required [23]. However, to better demonstrate the data rate achievable, 16-QAM is used for the calculations that follow. For 16-QAM, four bits per symbol are transmitted; for a symbol rate of 86 ksps, the resulting data rate is 344 kbps.

The calculation begins by determining the average SNR per bit available for the uplink from the SES. The average SNR per bit is given by

$$\frac{E_b}{N_o} = \frac{P_r}{N_o}\frac{1}{R} \tag{3.15}$$

where R is the data rate [17]. Substituting in the value calculated for P_r/N_o from Table 8 and the desired data rate of 344 kbps into Equation 3.15, we obtain the average E_b/N_o available as 12.0 dB. Next, the average energy required to transfer information at 344 kbps is calculated. Before the required energy is calculated, Equation 3.14 is converted from symbol error probability to probability of bit error. For gray coded MQAM, the relationship between probability of symbol error and probability of bit error is [25]

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$$P_b = \frac{P_s}{\log_2 M}.$$ (3.16)

Combining Equations 3.14 and 3.16, we get the probability of bit error for MQAM

$$P_b \leq \frac{4}{(\log_2 M)} Q\left(\sqrt{\frac{3kE_b}{(M-1)N_o}}\right).$$ (3.17)

From [14] the required probability of bit error for Inmarsat is 10^{-7}. Rearranging Equation 3.17 and substituting the values for the known variables, we get

$$\frac{10^{-7}(\log_2 16)}{4} \leq Q\left(\sqrt{\frac{3(4)}{16-1}\frac{E_b}{N_o}}\right)$$ (3.18)

which simplifies to

$$1 \times 10^{-7} \leq Q\left(\sqrt{\frac{4}{5}\frac{E_b}{N_o}}\right).$$ (3.19)

To obtain E_b/N_o, the aid of a Q-function table or a computer program like MATLAB is required. For the calculations that follow, MATLAB is used. The Q-function is defined in terms of the error function in MATLAB and is given by

$$Q(x) = \frac{1}{2}\left(1 - \text{erf}\left(\frac{x}{\sqrt{2}}\right)\right),$$ (3.20)

which can be inverted to yield

$$Q^{-1}(y) = \sqrt{2}\,\text{erf}^{-1}(1 - 2y)$$ (3.21)

The error function is defined as

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2} dt.$$ (3.22)

From Equation 3.21, where $y = 10^{-7}$, the inverse Q-function yields

$$Q^{-1}(y) = 5.1993.$$ (3.23)

From this result and Equation 3.19, E_b/N_o is found to be

$$\frac{E_b}{N_o} \geq 33.79 = 15.3 \text{ dB}$$ (3.24)

Notice that the required E_b/N_o (15.3 dB) is greater than the available E_b/N_o (12.0 dB) by 3.3 dB. This result indicates that due to lack of power the required probability of bit error of 10^{-7} cannot be achieved using 16-QAM. [23]

In order to mitigate the lack of power needed for a data rate of 344 kbps via 16-QAM, the obvious solution is to increase power. However, recall that there is only a limited amount of power available in Inmarsat for uplink transmissions. The more practical means of alleviating the lack of power is to use error correction coding. To be able to successfully achieve a probability of bit error of 10^{-7} at a data rate of 344 kbps via 16-QAM, an extra 3.3 dB of energy per bit is required. In the next section, it is shown that the lack of 3.3 dB in energy per bit can be compensated for through the use of FEC coding.

Recall from the Shannon limit calculations that the theoretical downlink data rate of 1.043 Mbps is much greater than the theoretical uplink data rate of 579 kbps. In order to truly optimize the link, the available power for both the upstream and downstream links needs to be maximized. The link budget reveals that more power is available from the satellite-to-ship link than from the ship-to-satellite link, maximizing the available power for both upstream and downstream links results in a downstream data rate that is significantly higher than the upstream data rate.

The satellite-to-ship link is analyzed in similar fashion as the ship-to-satellite link. However, because the P_r/N_o of the satellite-to-ship link is significantly greater than the P_r/N_o of the ship-to-satellite link, the calculations that follow show that a higher downstream data rate is achievable. To determine the maximum data rate for the satellite-to-ship link, the results for the spot beam link budget are utilized. Moreover, to demonstrate the data rate achievable for the satellite-to-ship link, the calculations are based upon a 256-QAM modulation instead of 16-QAM that was used in the earlier calculation. The downstream analysis begins by substituting the value of P_r/N_o from Table 11 into Equation

3.15, where the available E_b/N_o for a data rate of 688 kbps (86 ksps x 8) with 256-QAM is found to be 23.0 dB. [17, 23]

Next, using Equations 3.16 and 3.17, we get the required E_b/N_o for 256-QAM as

$$2\text{x}10^{-7} \leq Q\left(\sqrt{\frac{24}{255}\frac{E_b}{N_o}}\right). \tag{3.25}$$

From Equation 3.21, where y is set to equal $2\text{x}10^{-7}$, the inverse Q-function yields

$$Q^{-1}(y) = 5.0690. \tag{3.26}$$

Substituting this result into Equation 3.25, we get

$$\frac{E_b}{N_o} \geq 271.71 = 24.3 \text{ dB}. \tag{3.27}$$

Notice that the required E_b/N_o for the satellite-to-ship link is greater than the available E_b/N_o by 1.3 dB. This reveals that the satellite-to-ship link cannot effectively transmit at a data rate of 688 kbps. The next section shows that the lack of 1.3 dB can be compensated for with FEC coding. [17, 23]

E.   FORWARD ERROR CORRECTION CODING

Error correction coding "refers to the class of signal transformations designed to improve system performance by enabling the transmitted signal to better withstand the effects of various channel impairments, such as noise, interference, and fading" [17]. Error correction coding is very popular because it is typically a less expensive means of improving performance when compared to other methods such installing higher power transmitters and larger antennas. This is especially true for satellite communications where a modification for higher power transmitters and larger antennas equates to launching a new satellite. The improved system performance usually involves system trade offs such as error-performance versus bandwidth and power versus bandwidth [17]. For the case of Inmarsat, it is necessary to choose a coding technique that increases performance with minimal trade offs in power and bandwidth. Among

the popular coding techniques are block codes and convolutional codes. These techniques, however, improve system performance at the expense of expanding the bandwidth by an amount proportional to the reciprocal of the code rate [23]. Because of the limited bandwidth of Inmarsat, these coding techniques are not desirable options. A more viable option is to employ a combined coding and modulation scheme called trellis coded modulation (TCM), where the performance improvements come without expansion of the bandwidth or reduction in the effective information rate. [17, 23]

Trellis coded modulation is a technique in which coding is integrated into the modulation process by limiting the possible waveforms that can follow the transmitted waveform in order to maximize the free distance (minimum Euclidean distance) between coded signals. This is accomplished through a finite state encoder that decides the selection of signal waveforms for generating a coded signal sequence. To provide the redundancy required for coding and to maximize the free distance between coded signals, TCM employs signal set expansion. In the receiver, a soft decision maximum likelihood sequence decoder is employed to decode the signals [17, 23]. References [17] and [23] provide a further explanation of TCM.

The typical performance gains that can be achieved for trellis-coded MQAM are given in Table 12, where the *number of states* is related to the number of encoder memory elements, k_1 is the number of information bits that are encoded, $k_1 + 1$ is the combined number of information and code bits, and m is the number of information bits per symbol [23].

Observe from Table 12 that an uncoded 16-QAM is coded using 32-QAM. Error correction coding requires adding extra bits called parity bits to the message bits (information bits). Using block or convolutional codes, the addition of parity bits expands the bandwidth when the data rate is held constant. The bandwidth expands because the symbol rate increases to compensate for the

additional parity bits. For TCM, the parity bits are appended to the uncoded message by increasing the number of bits per symbol (signal set expansion).

Table 12.   Coding Gains for Trellis-coded MQAM (From [23])

Number of states	k_1	Code rate $\dfrac{k_1}{k_1+1}$	$m=3$ gain (dB) of 16-QAM versus uncoded 8-QAM	$m=4$ gain (dB) of 32-QAM versus uncoded 16-QAM	$m=5$ gain (dB) of 64-QAM versus uncoded 32-QAM	$m=\infty$ asymptotic coding gain (dB)
4	1	1/2	3.01	3.01	2.80	3.01
8	2	2/3	3.98	3.98	3.77	3.98
16	2	2/3	4.77	4.77	4.56	4.77
32	2	2/3	4.77	4.77	4.56	4.77
64	2	2/3	5.44	5.44	5.23	5.44
128	2	2/3	6.02	6.02	5.81	6.02
256	2	2/3	6.02	6.02	5.81	6.02

Increasing the number of bits per symbol allows the parity bits to be appended to the message bits without expanding the bandwidth. The bandwidth is not expanded because the symbol rate is kept constant; only the number of bits per symbol is increased [17].

From the calculations made in the previous section for the ship-to-satellite link, an extra 3.3 dB of energy per bit is required to transmit at a data rate of 344 kbps using 16-QAM. Observe from Table 12 that the coding gain of 32-QAM vs. 16-QAM is, depending upon the complexity of the encoder, from 3 to 6 dB.   This indicates that with trellis coded 32-QAM, the 3 dB of extra energy per bit cannot only be compensated for, but moreover, a margin of 3 dB is attainable. The calculations above only show that 344 kbps is attainable in the ship-to-satellite link, it does not by any means indicate that 344 kbps is the maximum data rate that can be achieved. The satellite-to-ship link can also be improved upon through forward error correction coding. Observe that the asymptotic coding gain from Table 12 is anywhere from 3 to 6 dB. Thus, the extra 1.3 dB of power needed to communicate at 688 kbps using 256-QAM can be easily compensated for using TCM. With the more advanced turbo codes, it may be possible to

approach the Shannon limit for both the ship-to-satellite and satellite-to-ship link [17]. Turbo coding is an advanced coding technique in which two coding schemes are employed together [17]. Such techniques, however, are beyond the scope of this thesis.

F.   CHAPTER SUMMARY AND CONCLUSION

In this chapter the maximum data rate achievable through Inmarsat was investigated. The link budget analysis revealed that the ship-to-satellite link limits the overall potential increase in the data rate of Inmarsat since it has the lowest P_r/N_o. Further findings indicate that the links between the satellite and the ship are most susceptible to channel impairments, and the links between the satellite and LES are not as susceptible to the effects of channel impairments due to the higher amount of power available. After determining the actual bandwidth and the received power of the system, the Shannon capacity was calculated for both the upstream and downstream links. The results revealed that the theoretical maximum data rate for the available power and bandwidth is significantly greater than the current data rate of 128 kbps. Furthermore, the results from the Shannon capacity calculations show that the current configuration of Inmarsat allows a SES to receive data from a LES at a significantly higher data rate than its ability to transmit data. The current Inmarsat system, however, does not take advantage of the high capacity of the downstream link, and only allows 128 kbps for both upstream and downstream links.

To make the most of the available bandwidth and power, a bandwidth and power efficient modulation scheme was chosen. In the investigation of the most popular modulation schemes, it was found that MQAM was the most promising candidate. With a modulation scheme chosen, the maximum data rate achievable using MQAM was determined. The analysis of the ship-to-satellite link showed that with the available power, 16-QAM cannot support a data rate of 344 kbps at the required probability of bit error rate of 10^{-7} [14]. To compensate for the lack of power, it was determined that error correction coding was

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necessary. Among the various types of coding schemes, trellis coded modulation was chosen because it increases performance without expanding the bandwidth. Using trellis coded 32-QAM, we found that a data rate of 344 kbps can be achieved through the ship-to-satellite link. The analysis of the satellite-to-ship link revealed that by using 256-QAM a data rate of 668 kbps is also achievable through error correction coding. Using turbo codes, both the upstream and downstream links are able to approach the Shannon limit [17].

The analysis presents a very important discovery for the implementation of a dynamic data rate link. Because the links between the satellite and SES are most susceptible to channel impairments, only the channel between the ship andsatellite should be monitored in the determination of whether to increase or decrease the data rate. The next chapter discusses how to implement a dynamic link over Inmarsat.

IV. ACHIEVING A DYNAMIC LINK

A. CHAPTER INTRODUCTION

The previous chapter revealed that the available power and bandwidth for both upstream and downstream links are being underutilized by the current Inmarsat system configuration. With the application of turbo coding, data rates approaching the Shannon limit can be achieved due to the higher coding gains available with turbo codes. The envisioned Inmarsat system, however, does not simply improve throughput through an increase in the static data rate; it is rather a system that improves the overall throughput by optimizing the transmission bit rate for different channel conditions. The envisioned Inmarsat system is a dynamic link system that can determine the maximum data rate based upon measured parameters and communicates at the determined maximum data rate while maintaining a constant probability of bit error. To implement the envisioned system, many challenges must be overcome. The major challenges are changing data rates without exceeding the allocated bandwidth, monitoring channel conditions for determining the maximum data rate possible, and successfully modulating and demodulating a variable data rate transmission.

In this chapter the challenges aforementioned are investigated. Section B addresses methods of changing data rates. Section C addresses methods for determining the optimum data rate for the channel, and section D proposes two methods of demodulating a variable data rate transmission, with greater emphasis on the recommended method. In section E, problems regarding the synchronization of the encryption equipment connected to the modem are addressed.

B. VARIABLE DATA RATE

1. Varying the Symbol Rate

To achieve a dynamic link it is necessary to have a means of varying the data rate. There are two methods of varying the data rate that are commonly

found in literature, each with their individual advantages and disadvantages. One way of varying the data rate is to vary the symbol rate while keeping the same modulation scheme. Because symbols represent bits, as the rate of symbols transmitted through the channel increases so does the data rate. For example, let the modulation be QPSK and the symbol rate be 32 ksps. For QPSK each symbol carries two bits of information; at a symbol rate of 32 ksps, the throughput is 64 kbps. The relationship between symbol rate and data rate is

$$R = R_s k \tag{3.28}$$

where R is the data rate in bits per second, R_s is the symbol rate, and k is the number of bits per symbol [17]. As can be observed from Equation 4.1, varying the symbol rate has the advantage of allowing precision control of the data rate. Varying the data rate by varying the symbol rate, however, does not make the most efficient use of bandwidth. The relationship between null-to-null bandwidth and symbol rate for QPSK and MQAM is [17]

$$W = 2R_s = 2\frac{R}{k}. \tag{3.29}$$

Note that the channel bandwidth of the signal is proportional to the symbol rate. When the symbol rate decreases, the system underutilizes the available bandwidth because the signal does not occupy all of the available bandwidth. On the other hand, if the system were to upgrade to a higher power transmitter, the system cannot take advantage of the increased SNR because the maximum symbol rate is constrained due to bandwidth limitations. The potential underutilization of bandwidth and the maximum data rate being contingent upon the available bandwidth are serious drawbacks to simply varying the symbol rate and are not desired qualities for the envisioned system.

2. Varying the Level of Modulation

A more viable method of varying the data rate for Inmarsat is to vary the number of bits transmitted per symbol while keeping the symbol rate constant; i.e., vary the level of modulation [26]. For example, let the modulation scheme

employed be QPSK and let the symbol rate be kept constant at 64 ksps. In this case, the throughput of the system is 128 kbps because each symbol carries two bits of information. Contrast this with 8-QAM where each symbol carries three bits of information. At a symbol rate of 64 ksps, the throughput of the system is three times the symbol rate (196 kbps). From the examples given it is clear that by doubling or halving the modulation level, the number of bits per symbol is increased or decreased in increments of one bit per symbol. Note that unlike varying the symbol rate, varying the modulation level changes the data rate without expanding the bandwidth because the symbol rate is kept constant. This makes varying the modulation level more desirable for the envisioned system because the bandwidth is more efficiently utilized by keeping the symbol rate at the maximum rate allowed for the available bandwidth.

Varying the modulation level also has the advantage of maximizing the data rate by optimizing the use of the power available in the system. When more power is available, the data rate can be increased while maintaining a constant probability of bit error by simply increasing the MQAM level. Conversely, when less power is available, the data rate is decreased to maintain a constant probability of bit error by simply decreasing the MQAM level. From this concept, it is evident that varying the level of modulation can make optimum use of the available power because it allows the envisioned system to transmit at the maximum data rate that the available power can support. At times when channel integrity is good, the received power is high and the envisioned system can operate at the highest modulation level. In poor channel conditions, the received power is low, and the system will operate at a lower modulation level. For the proposed system, the MQAM levels are varied among QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, 256-QAM and 512-QAM. For ease of reference, the levels of MQAM and the varying data rates that can be achieved are tabulated in Table 13. [17, 23]

Table 13.   Data Rates at Different Modulation Levels Using 86 ksps and No Forward Error Correction Coding.

QAM Level	Data Rate	Required E_b / N_o
QPSK	172 kbps	11.3 dB
8-QAM	258 kbps	13.3 dB
16-QAM	344 kbps	15.3 dB
32-QAM	430 kbps	17.4 dB
64-QAM	516 kbps	19.6 dB
128-QAM	602 kbps	21.9 dB
256-QAM	688 kbps	24.4 dB
512-QAM	774 kbps	26.8 dB

The reader may question why a level greater than 16-QAM is proposed. Chapter III showed that the maximum data rate that the channel can support without turbo coding is approximately 344 kbps. Secondly, it was stated in Chapter II that the maximum data rate that the KG-84A can support is 256 kbps. The reason why there are levels of modulation in the proposed system greater than 16-QAM is because it is desired that the envisioned system be compatible to future upgrades. If larger antennas, more powerful transmitters, and faster cryptologic equipment are installed, the proposed system's design can take advantage of such upgrades through the use of higher levels of modulation. Designing the system with high levels of modulation is a practical provision since a new and more powerful satellite (Inmarsat IV) will soon be used for U.S. Navy communications. The Inmarsat IV satellites have greater power than its predecessors. The proposed system will be able to take advantage of the increased power available, and a data rate greater than 344 kbps can be achieved [4].

Varying the level of modulation is clearly the most suitable method for Inmarsat to achieve a dynamic data rate. Because Inmarsat is operating under bandwidth and power constraints, coding is required as was explained in Chapter III. To integrate trellis coded modulation into a variable data rate system, the levels shown in Table 13 are increased by one level to achieve the desired data rate with a code rate of $k/k+1$. Table 14 shows how to integrate coding to

achieve a specific bit rate. The next challenge that needs to be addressed is to determine exactly when the proposed system should change data rates. The next subsection addresses this issue.

Table 14.   TCM Encoded Variable QAM at 86 ksps.

Base Level QAM (uncoded)	TCM Encoded QAM (rate $k/k+1$)	Data Rate (kbps)
QPSK	8-QAM	172
8-QAM	16-QAM	258
16-QAM	32-QAM	344
32-QAM	64-QAM	430
64-QAM	128-QAM	516
128-QAM	256-QAM	602
256-QAM	512-QAM	688
512-QAM	1024-QAM	774

C.   DATA RATE THRESHOLDS

For a dynamic link to be effective, the system needs to be able to determine the optimum time to switch between the different modulation levels. There are two basic building blocks for determining the optimum time to switch data rates. The first basis for switching data rates is through the measured bit error rate at the receiver, defined in the literature as the error detector approach. The second basis for switching data rates is through the received signal strength indicator approach (RSSI). [27]

1.   Error Detection Approach

In the first method, the receiver monitors the bit error rate resulting from channel degradations. When the measured bit error rate is determined to be better than the required bit error rate, the level of modulation is increased. When the measured bit error rate indicates an unacceptable number of errors, the modulation level is decreased to maintain a specified bit error rate [27]. Varying the level of modulation appropriately allows the system to mitigate changes in bit error rate because as the modulation level is decreased, the required SNR to

maintain a specific bit error rate also decreases. The opposite is true when the modulation level is increased (see Table 14) [17].

One way to monitor the bit error rate is to insert a known bit sequence at a specified position in a block of bits. The known bit sequence can be inserted anywhere in the block, typically at the end or beginning of the block, as long as the receiver knows where the known bit sequence is. The receiver compares the received sequence to the expected sequence stored at the receiver. From this comparison the receiver is able to estimate the bit error rate. This method, however, increases the overhead of the system because the symbols used to transmit the known bit sequence occupy bandwidth that could be used to transmit information bits. Furthermore, the number of bits required for the known sequence is often very large due to the small bit error rate being estimated.

A more effective method of measuring the bit error rate is to use the coding scheme employed to count the number of errors in a block. If the system is already using coding to improve the performance of the system, it is superfluous to insert a known bit sequence because coding schemes insert parity bits for both error correction and detection. The error detection approach performs poorly when compared to the received signal strength approach. The error detection approach gives inferior results because it is passive, in the sense that it decreases modulation levels after a specific error threshold is detected. Because it can only respond after an error threshold is reached, it is often too late for the system to respond and maintain a constant bit error rate [27]. For a data rate switching method to be effective in a dynamic link system, the switching method should be able to anticipate when the channel is going to degrade before the corruption from the channel can cause bit errors. A technique that can anticipate channel degradation is the received signal strength indicator (RSSI) approach [27].

Although the error detector approach is inferior to the RSSI approach, it is possible that the error detector approach can be used to anticipate channel conditions for switching modulation level. Consider a decoder that can measure

the input bit stream's bit error rate as it corrects errors. If the bit error rate at the output of the decoder is linearly related to the bit error rate at the decoder's input, it may be possible to determine the switching threshold based upon the measured input bit error rate at the decoder. For instance, consider a bit stream with a bit error rate of 10^{-5} at the input of the decoder. Because the decoder can correct some errors, the bit error rate at the decoder's output is 10^{-7}. If the bit error rate at the input of the decoder degrades to 10^{-3}, the decoder is no longer able to maintain a bit error rate of 10^{-7} at its output. If it is desired to maintain a bit error rate of 10^{-7} at the decoder's output, the threshold for switching the level of modulation can be set to a value that is a little lower than the value of input bit error rate that yields the maximum permissible output bit error rate. For the example above, if it is determined through analysis and simulation that an input bit error rate greater than or equal to 10^{-3} yields an unacceptable bit error rate at the output of the decoder, the threshold for switching levels could be set to an input bit error rate of 10^{-4}. In this way, the level of modulation is decreased before an unacceptable number of errors occur. Anticipating the channel condition in this way can eliminate the mistake shown in [28] and discussed in [27] where the bit error rate was allowed to reach an unacceptable bit error rate before the level of modulation was switched. The assertions made about using the error detector approach to anticipate channel conditions are yet to be investigated through simulation and experiments.

2.   Received Signal Strength Indicator Approach

The RSSI approach is based upon the received signal strength. When channel conditions are poor, the signal at the receiver is weak. Conversely, when channel conditions are good, the received signal is strong. Depending upon the signal strength received, the modulation level is either increased, decreased, or left unchanged. For low signal power, the modulation level is decreased. When signal power is high, the modulation level is increased to achieve a higher data rate while maintaining a bit error rate that does exceed the

maximum permissible bit error rate. One way of obtaining the switching levels can be found from the bit error rate vs. SNR curves. In Figure 20 the bit error rate vs. SNR of an M-QAM modulator is shown. To determine the thresholds for switching modulation levels, a horizontal line corresponding to the maximum permissible bit error rate is drawn. A broken vertical line is drawn from the intersection of each of the QPSK, 8-QAM, and 16-QAM curves and the horizontal line. The point at which this broken vertical line intersects the x-axis defines the required SNR needed to successfully transmit at the specified bit error rate. At the bit error ratio of interest (10^{-7}), a solid vertical line is drawn between the level curves. The point at which the solid vertical line intersects the x-axis signifies the SNR threshold between the two levels of modulation. Observe that the level is switched before the minimum SNR for the bit error rate of interest is reached. This is done because if the level switching occurs exactly at the minimum SNR, the likelihood of maintaining the bit error probability decreases. From Figure 20, if E_b / N_o is between 11.2 dB and 12.1 dB then the modulation scheme should be QPSK. If E_b / N_o is between 13.1 dB and 14.1 dB then the modulation scheme should be 8-QAM, etc. [27]

D.   DYNAMIC LINK SYSTEM MODEL

Probably the greatest challenge in implementing a dynamic satellite link is the establishment of an efficient protocol between the transmitting and receiving modems. For the proposed system, the data rate is varied by varying the level of MQAM at the modulator and the demodulator. A problem arises when the channel condition degrades or improves and there is a need to change data rates. This is because when a modulator changes from one level to another, the demodulator must determine the proper level of modulation. For instance, at the start of transmission, if the transmitting modem is using 16-QAM, but because the channel has degraded a switching threshold has been reached, then it is

necessary to decrease the modulation level to 8-QAM. When the modulator switches from 16-QAM to 8-QAM, the demodulator at the receiver must be informed.
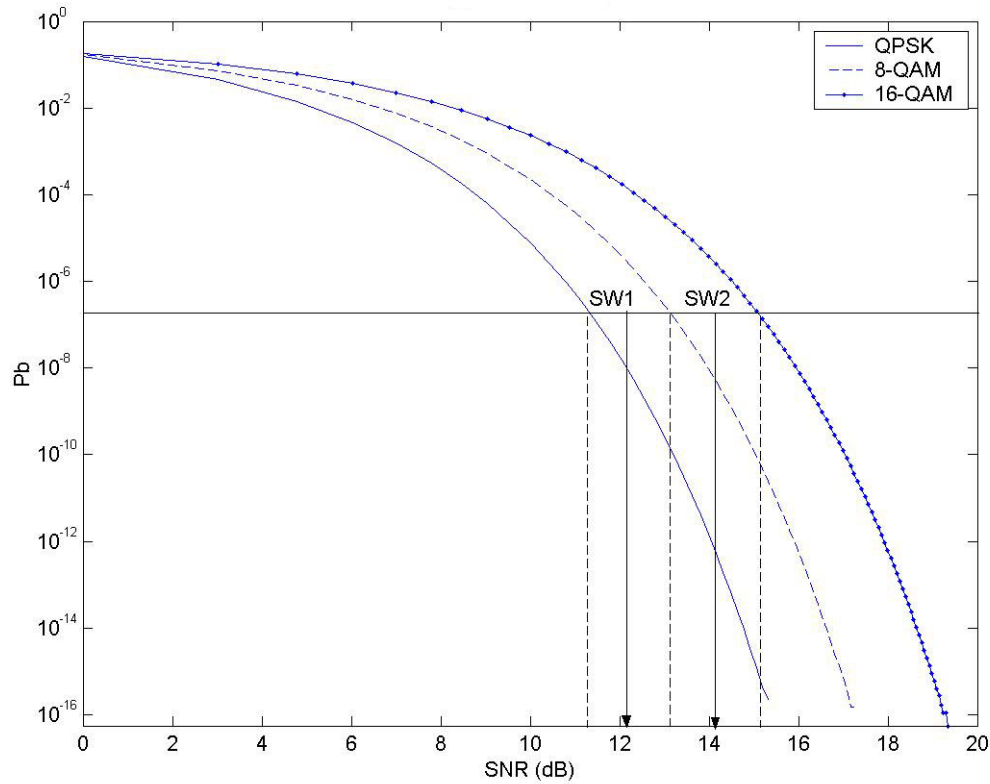
Figure 20.   RSSI Level Switching Approach (After [27])

Otherwise, the demodulator will attempt to demodulate an 8-QAM symbol as if it were a 16-QAM symbol. This would result in catastrophic degradation of the data being received. For this reason, it is essential that protocols between the modulator and demodulator be established.

1.   Informed Demodulator Approach

The most promising approach found in the literature that can be applied to establish modulation level synchronization between the two modems is through the informed demodulator approach. In this approach, symbols to be transmitted in a specific level of modulation are grouped into a block of symbols. At the

beginning of each symbol block, control bits are inserted using a set of symbols. Control bits are defined as bits inserted to a block to convey information from the transmitting modem to the receiving modem. The receiver needs to demodulate the control bits to determine the level of modulation. To ensure proper demodulation of the control bits, the modulation level least susceptible to channel degradation is used. Therefore, the control bits are always transmitted using uncoded QPSK while the remainder of the block is transmitted using whatever TCM MQAM level is indicated by the control bits. Uncoded QPSK is chosen over TCM QPSK because, as is shown later in this chapter, QPSK combined with majority voting delivers control bits with significant reliability without the complexity of TCM QPSK. With control bits, at the transmitter can inform the demodulator of the level of modulation employed by the transmitter for the remainder of the block. [28]

Recall from the previous subsection that the switching thresholds established are the basis for assessing channel integrity and, thus, the level of modulation. Also recall from Chapter III that the links between the satellite and the ship are most susceptible to channel degradation because the satellite-to-ship and ship-to-satellite links have lower signal power when compared to the satellite-to-LES and LES-to-satellite links. Because the links between the satellite and the ship are more susceptible to channel impairments that degrade the bit error probability of the received signal, only the channel between the satellite and the ship are monitored in order to determine the maximum data rate for forward and reverse communications. In the informed demodulator approach, the transmission received by the ship from the satellite is used to assess the channel integrity from which the level of modulation is determined for subsequent transmission from the ship and from the LES. In case the channel between the satellite and LES degrades more than the channel between the satellite and the ship, because of significant power margins available to the links between the satellite and LES, it is still assumed that the links between the satellite and LES are able to maintain communication well before there is a loss of communication

between the satellite and ship. It is suspected that the links will degrade by the same amount because Inmarsat communicates between the satellite and the ship in L-band frequencies in both forward and reverse directions, and the satellite and LES communicate in the C-band in both forward and reverse directions [1]. If the links degrade by the same amount, and if the channel degradation is severe enough, the ship-to-satellite and satellite-to-ship links will be unable to maintain the required probability of bit error well before the satellite-to-LES and LES-to-satellite links are unable to maintain the desired probability of bit error.

The proposed protocol enables a satellite link to send and receive information at different rates. This is a major advantage of the proposed system because the throughput is maximized for both the forward and reverse direction of communication, resulting in an overall improvement in spectral efficiency. This approach, however, only works with duplex transmission (two way communication) because the approach depends upon the ship's receiver to determine the data rate for following transmissions. In simplex transmission (one way communication), although the ship's received signal can be used to monitor channel conditions, the LES receiver cannot make use of this information because the ship's terminal cannot transmit in the reverse direction. [28]

As mentioned earlier, it is essential that the demodulators know of the modulation level of the received signal, otherwise, successful data transmission is impossible. When a new modulation level is determined at the ship's receiver, the transmitter sends a set of symbols containing the control bits to inform the demodulator at the earth station of the new MQAM level. The control bits are encoded using two uncoded QPSK symbols [28]. Table 15 below shows a possible configuration of how the control bits can represent the levels of QAM using two uncoded QPSK symbols. Note that the bits corresponding to the MQAM levels are assigned arbitrarily.

Table 15.   QAM Level Representation Using Two QPSK Symbols

QPSK Symbol 1	QPSK Symbol 2	MQAM Level
00	00	8-QAM
00	01	16-QAM
00	10	32-QAM
00	11	64-QAM
01	00	128-QAM
01	01	256-QAM
01	10	512-QAM
01	11	1024-QAM

It is necessary to use two symbols because the eight different MQAM levels cannot be represented by two bits alone. With two QPSK symbols, sixteen values can be represented. It is worth noting that because it is extremely critical that the control bits relaying the MQAM level be received without errors, the modulation level which is least susceptible to channel degradation is used to send the control bits. For the proposed system, this level of modulation is QPSK. Consider the situation where 16-QAM is used to encode the control bits. If, due to adverse channel conditions, a switching threshold has been approached signifying a level decrease from 16-QAM to 8-QAM. In this case, the control bits sent with 16-QAM to inform the demodulator of the change in level will have a low probability of being received correctly. This is because 16-QAM requires more SNR for successful reception than the SNR available; thus, the probability is unnecessarily high that the system will not be able to switch to 8-QAM, and the entire block of data will be lost.   To further ensure that the control bits are received correctly, the two QPSK symbols signifying the level of modulation are transmitted three times, after which majority voting is performed in order to increase the probability of correctly determining the level of modulation. [28]

The probability of losing a block due to misreading the control bits is analyzed by considering a QPSK symbol as two BPSK bits, one on the in-phase channel and one on the quadrature channel. Therefore, the six QPSK symbols can be analyzed as twelve BPSK bits. Recall that two QPSK symbols signifying the modulation level are transmitted a total of three times, after which majority

voting is performed to increase the probability of correctly determining the modulation level. The two QPSK symbols repeated twice (first two symbols, repetition 1, repetition 2) correspond to twelve bits grouped into three control blocks containing four bits. Consider if the first block contains bits 0111, the second block contains bits 1111, and the third block contains bits 0111. After majority voting, the modulation level is 1024-QAM as designated by the control bits 0111 in Table 15. Observe that if two control blocks each have one bit error, the control bits signifying the level of modulation level is unlikely to be determined correctly. For example, if the transmitted control block is supposed to be 0111 and the three control blocks received are 0111, 0011 and 0110, then there is only a one in three chance of correctly determining the modulation level. Because bit errors are independent (a consequence of the AWGN channel), the twelve BPSK bits can be analyzed independently. If the probability of a single channel BPSK bit being received in error is p, since bit errors are independent, then the probability that two control blocks each have one bit error can be considered as having two bit errors out of three bits, the three bits corresponding to the number of blocks. The probability that at least two out of three bits are received in error is

$$\Pr\{\text{control bit error}\} = 3p^2 + p^3 \approx 3p^2, \tag{3.30}$$

where p is equal to 10^{-7}, the worst case probability of channel bit error currently maintained by Inmarsat for ship and LES communication at a data rate of 128 kbps [14]. If at least two out of the three control blocks must receive all four bits correctly to avoid control block error, then the probability of receiving the control block correctly is

$$\Pr\{\text{receiving control block correctly}\} \approx (1\text{-}3p^2)^4. \tag{3.31}$$

and the probability of receiving the control block incorrectly is

$$\Pr\{\text{control block error}\} = 1\text{-}(1\text{-}3p^2)^4 \approx 12p^2 = 1.2\text{x}10^{-13}. \tag{3.32}$$

It is not a certainty that two control bit errors cause a control block error. For example, if the received blocks contain the bits 0111, 0111 and 0100, a control block error does not occur after majority voting. It is also not required that two control blocks be received correctly to avoid control block error because there

are less than 16 distinct control blocks. There is also a one in three chance of avoiding control block error when two control blocks each have at least one bit error. Furthermore, the calculations above only take into account the worst case probability of bit error. It is expected that Inmarsat operates at a better probability of bit error due to margin provisions. Therefore, the result calculated above can be taken as an upper bound, and

$$\Pr\{\text{control block error}\} \leq 1.2 \times 10^{-13}$$

Since there are 3.15×10^7 seconds/year, the probability of having a single control block error in one year is less than 10^{-6} if the control blocks are transmitted once per second. [23, 29]

Figure 21 illustrates how the information block and control symbol block is set at the LES transmitter; in the figure, the block length is arbitrarily set to 258 x 10^5 symbols, corresponding to 5 minutes at 86 ksps. Note that the level of modulation can only switch at the beginning of each block of symbols. If the control bit symbols are decoded incorrectly and the demodulator demodulates at a different level, all the data are lost until the control symbols in the next block are received and decoded correctly.

Figure 21.   LES Transmitter's Block Framing Structure (After[28])
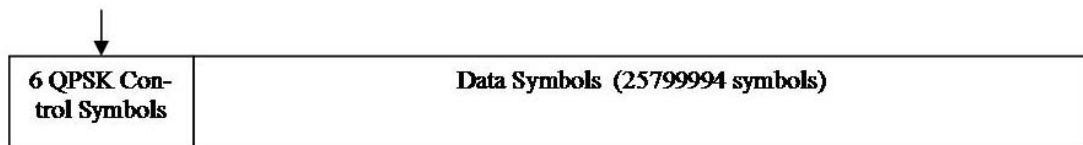
The implementation of a dynamic link transceiver using the informed demodulator approach together with the RSSI switching technique is shown in Figure 22. The front end of the ship's transceiver receives the symbol waveforms at the carrier frequency and down converts them to baseband signals. After the baseband signals are recovered, a time-division demultiplexer

separates the first six symbols, the control symbols, from the rest of the symbol block. The QPSK control symbols are demodulated and undergo majority voting to recover the control bits that represent the level of MQAM demodulation for the rest of the block. The rest of the block is separated by the time-division demultiplexer and sent to a variable level MQAM demodulator which demodulates the remaining symbols based upon the control bits. The output of the demodulator, now in digital form, is sent to the KG-84 for decryption. [28]
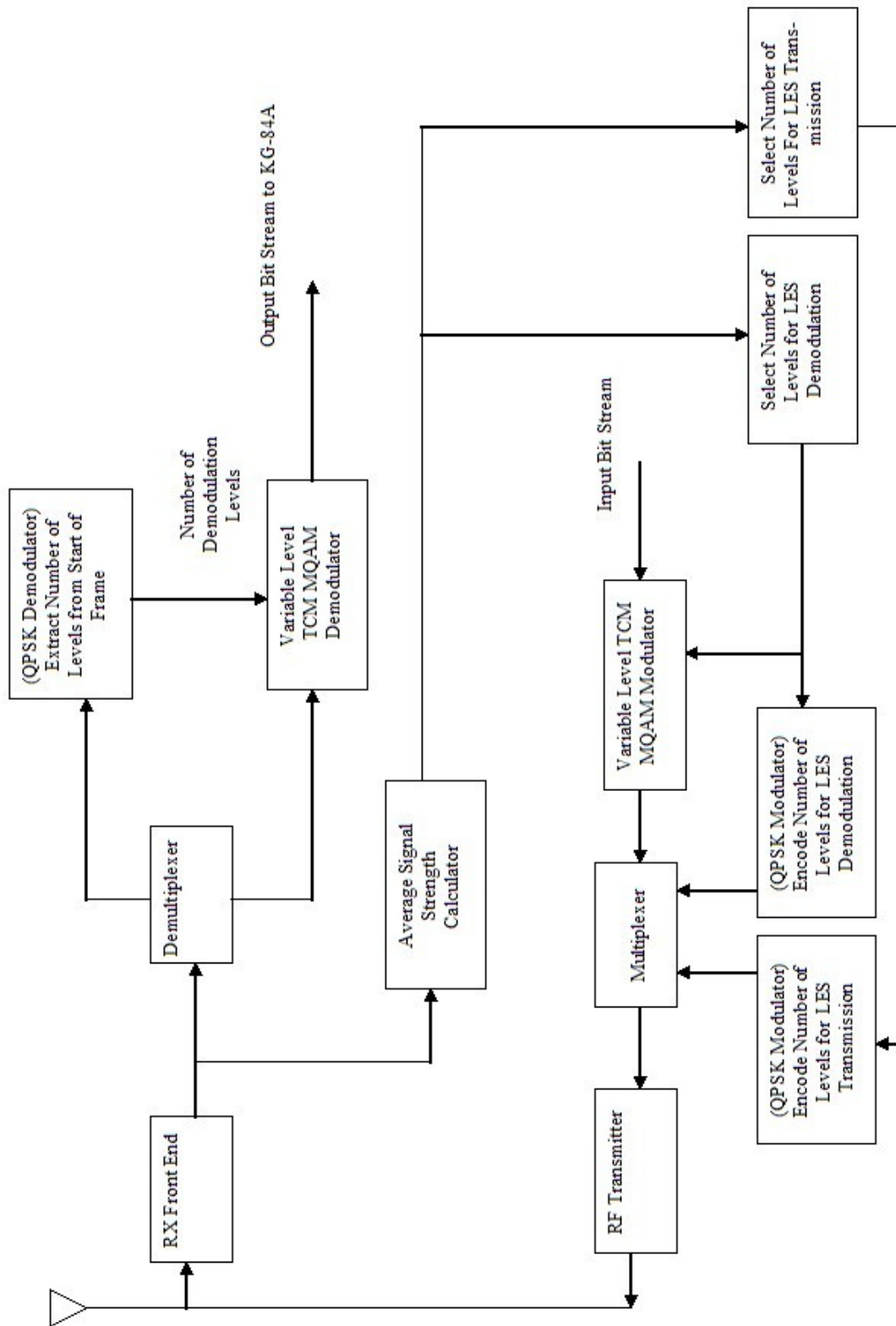
Figure 22.   Ship's Transceiver Block Diagram (After [28])

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The baseband signals recovered by the ship's receiver are also processed by the average signal strength calculator to determine the average signal strength of the whole block. At the end of each block, the average signal strength calculated is sent to two level selection circuits that select the level of modulation for the ship and LES transmitters based upon the established thresholds for level switching. Recall from Chapter III that the links between the satellite and the ship are the most susceptible to channel impairments. To monitor the channel conditions between the ship and the satellite for forward and reverse communications, the received signal from the satellite is used to monitor channel integrity. The channel is monitored through the RSSI approach. Note that the thresholds are different for the ship-to-satellite and satellite-to-ship links because of the available power difference revealed from the link budget. To establish effective thresholds for modulation level switching, simulations and experiments must be undertaken. From the results of Chapter III, the thresholds for level switching should be established so that the LES-to-ship link communicates at a much higher data rate than the ship-to-LES link. The level of MQAM determined by the level selection circuit for ship-to-LES transmission is sent to a variable level MQAM modulator and a QPSK modulator. The variable level MQAM modulator modulates the outgoing data corresponding to the level determined by the level selection circuit. The QPSK modulator encodes the MQAM level of the outgoing data using six QPSK control symbols at the start of the symbol block; these control symbols inform the LES demodulator of the received signal's modulation level. The second level selection circuit determines the QAM level for subsequent LES-to-ship transmission based on a different set of threshold values.

The MQAM level for subsequent LES-to-ship transmission is also encoded by a QPSK modulator using six QPSK symbols with majority voting. A time-division multiplexer combines the signals from the variable level MQAM modulator and the two QPSK modulators. After the three signals are multiplexed, the aggregate signal from the multiplexer is sent to the radio

transmitter for up conversion and transmission over the channel. Figure 23 illustrates how the symbol block is arranged by the ship's transmitter. [28]

The LES transceiver demodulates the symbol from the ship's transmitter in a similar manner. Figure 24 illustrates how the LES transceiver operates. The front end of the LES's transceiver receives the symbol waveforms at the carrier frequency and down converts them to baseband signals. After the baseband signals are recovered, a time-division demultiplexer separates the received signal into three parts. The first set of QPSK control symbols are demodulated and undergo majority voting to recover the control bits that represent the level of MQAM for the demodulation of the data symbols.

Majority voting applied to QPSK symbols to determine QAM level for LES demodulation.

6 QPSK Control Symbols	6 QPSK Control Symbols	Data Symbols (25799988 symbols)

Majority voting applied to QPSK symbols to determine QAM level for LES modulation.
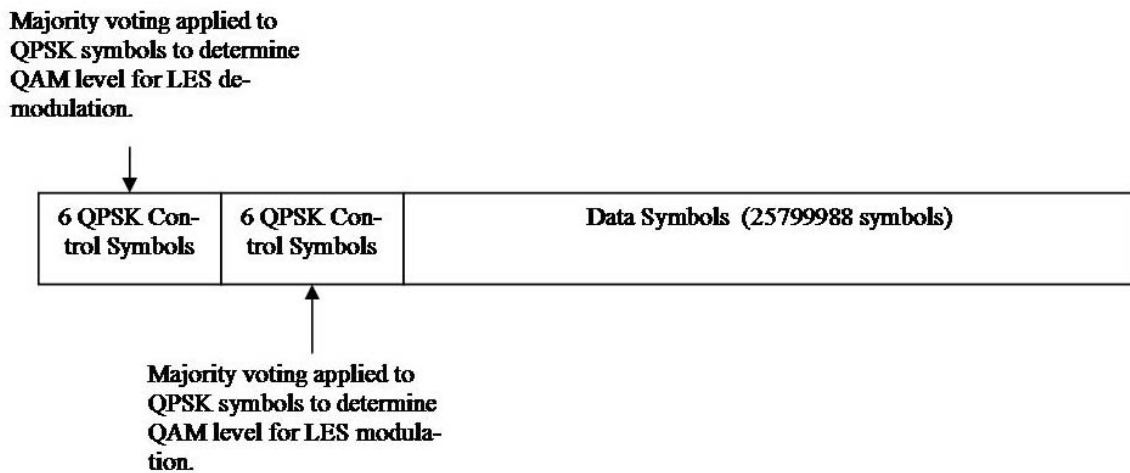
Figure 23.   Ship's Transmitted Symbol Block

The data symbol block is sent from the demultiplexer to a variable TCM MQAM demodulator that demodulates the data symbols based upon the received control bits. The output of the variable level TCM MQAM demodulator is in digital form for further processing by the LES. The second set of control symbols is demodulated and also undergoes majority voting for recovery of the control bits that represent the level of MQAM for subsequent LES transmission. After recovering the MQAM level for LES transmission, a signal is sent to inform the variable TCM MQAM modulator of the new modulation level. A QPSK modulator

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also receives the recovered MQAM level and encodes the MQAM level into six control symbols so as to inform the ships demodulator of the modulation level.
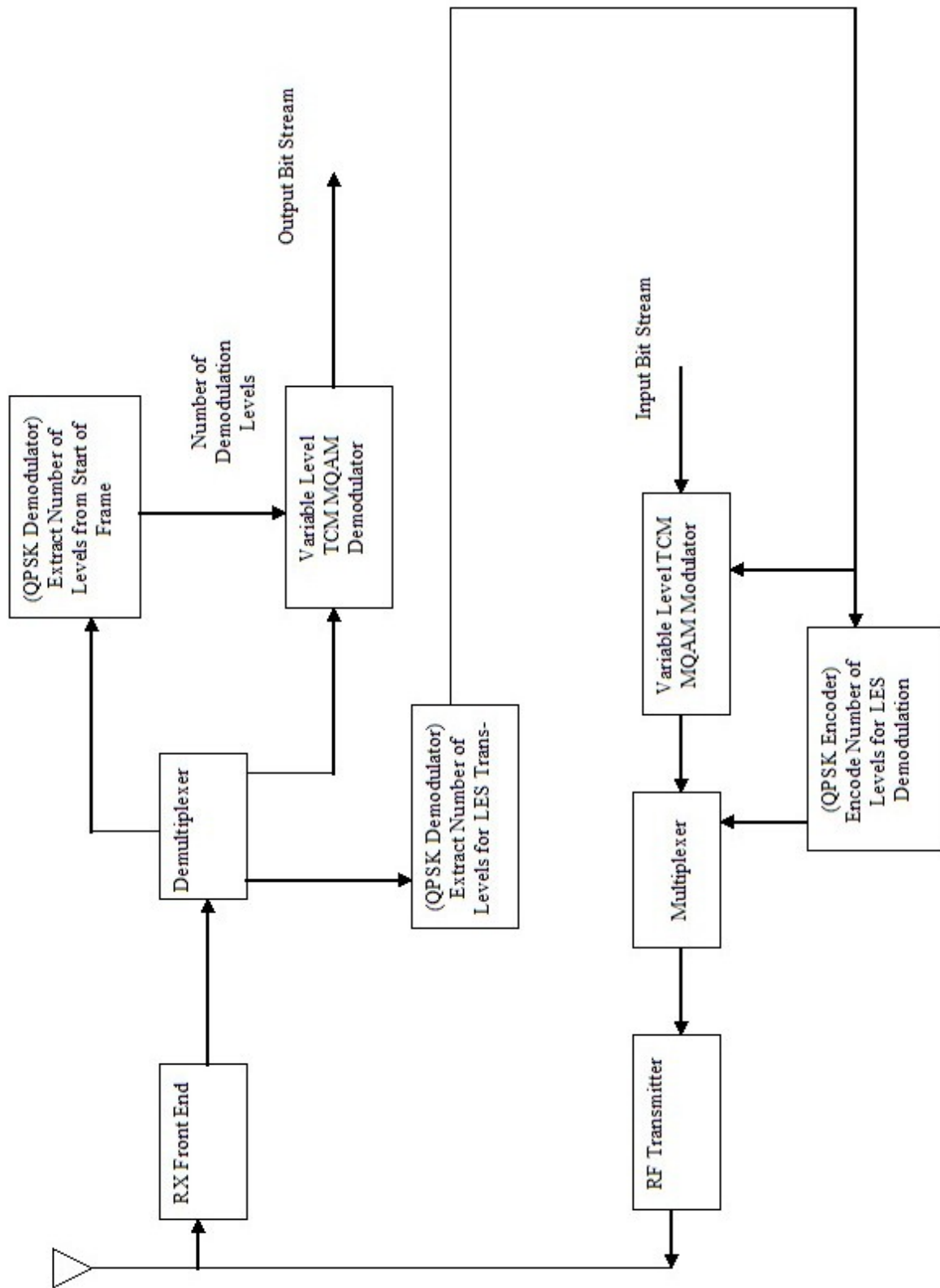
Figure 24.   LES Transceiver Block Diagram (After [28])

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The encoded QPSK control symbols are then multiplexed together with the inputs from the variable TCM MQAM modulator. The aggregate output from the multiplexer is sent to the RF transmitter for transmission into the channel. Figure 21 illustrates how the symbol block from the LES is arranged. [28]

It is worth noting that inserting control bits does not significantly decrease the total throughput. Furthermore, any throughput loss is overcome by the increased data rate made possible by varying the modulation level; by increasing the length of the symbol block, the throughput degradation is further minimized. For Inmarsat, it is not necessary to constantly change data rates because the channel is not expected to change rapidly. A reasonable amount of time to monitor channel conditions before switching data rates is estimated to be about five minutes. If the switching period is set to five minutes at any level of modulation, an extremely minor bit error degradation of 4.65×10^{-5} % is calculated. If it is desired to further reduce the throughput degradation, a longer switching value is required. [28]

2. Blind Demodulator Approach

Unlike the informed demodulator approach, the blind demodulator approach does not require control bits to determine the level of modulation. The blind demodulator instead receives a stream of symbols (128 symbols minimum) and stores the phase and amplitude properties of the received signals in a buffer. After the set of symbols are all received and stored in a buffer, the demodulator determines the constellation used by the transmitter by either the radius only technique [30] or the Radon transform [31]. After the constellation size is determined, the demodulator can continue to demodulate the received signal by assigning bits to the received signals.

This approach does not have a significant advantage of avoiding the throughput degradation resulting from the application of control bits. The main advantage of this approach is that it can be applied to both simplex and duplex transmission. On the other hand, this approach has the disadvantage of greater

system complexity, and its reliability is limited to a constellation size of only 256 levels due to difficulties in identification, especially in the presence of additive noise or incomplete equalization. [30, 31]

Although the blind demodulator approach has some advantages, its advantages are not significant when compared to those of the informed demodulator approach. Inmarsat is typically used for duplex transmission, and as discussed earlier, the throughput degradation arising from control bits is very minute because of the large symbol block.   For these reasons, and because the reliability of the blind demodulator is limited by a constellation size of 256 levels, it is deemed that this is not the best approach for a dynamic link in Inmarsat. Hence, this thesis will not go into further detail on the blind demodulator approach.

E.   KG-84A SYNCHRONIZATION

A matter worthy of close consideration is the effects of the delay caused by the six control symbols at the output of the variable MQAM demodulator. This is of concern because the KG-84A operating in synchronous mode requires a continuous bit stream for proper operation. In the proposed system, the six symbols used to encode the control bits cause a delay of at least 94 μs

$\left(t_{delay} = 6 \text{ symbols}/(6400 \text{ symbols/sec}) = 94 \; us \right)$. This delay requires the KG-84A to wait 94 μs at the end of each symbol block before the bit stream can continue at the output of the variable MQAM demodulator. This delay may cause loss of synchronization between the two KG-84A's at different ends of the channel because the receiving KG-84A expects a bit stream to be present at the time of the delay. A possible way to overcome the problems caused by the delay is to operate the KG-84A in asynchronous mode where the KG-84A can frame the bits being sent and received through start and stop bits. By framing the data bits corresponding to the length of the symbol block, the KG-84A knows that it has to wait at the end of each symbol block before it can expect the bit stream to continue at the output of the demodulator. [12]

The delay may also be surmounted in synchronous mode by making provisions for the modem to insert stop transmission messages (STM) at the end of each symbol block. STMs are bits used to inform the KG-84 that the bit stream being received has ended. The KG-84A recognizes these STM's and no longer expects a bit stream during the control symbol delay. For the next block of incoming bits, the KG-84A initiates synchronization as it does at the beginning of each transmission. In this manner the KG-84A maintains synchronization. Like the application of control bits, the insertion of STMs causes decreased throughput, but as long as the symbol block is large, the throughput degradation caused by bit insertion for the KG-84A is small. [12]

Another issue that must be addressed is the synchronization of the KG-84A's clock to an input bit stream that varies in data rate. When the data rate changes because of the different levels of MQAM employed, the bit stream at the output of the variable MQAM demodulator also varies in bit rate. If the clock of the KG-84A is not properly adjusted as the bit rate varies, the KG-84A will not be able to properly decrypt the incoming bit stream because its clock is out of synchronization with the input bit stream. Fortunately, the KG-84A's design makes provisions for controlling its clock by means of an external clock, allowing the KG-84A to be "a data rate change device" [12]. Because of this feature of the KG-84A, as the bit rate changes, the clock of the KG-84A can be adjusted to correspond to the appropriate bit rate. The KG-84A's design also makes provisions for a variable data rate input by providing the KG-84A the capability to phase-lock its receiver's internal clock (having 1.8 parts per million accuracy) to the incoming data. This capability allows the KG-84A to automatically detect the incoming bit stream's data rate and adjust its clock to the corresponding data rate. Thus, there are two possible methods of maintaining synchronization for the proposed system. [12]

It is important to understand why the system model proposed for implementing a dynamic data rate link is well suited for Inmarsat. This is because the problems arising from the delay caused by the insertion of control

bits can be surmounted as explained earlier. Furthermore, notice that the inserted control bits are not allowed to enter into the KG-84A. This is an important feature of the design because inserting bits into the receive KG-84A that were not generated by the crypto device at the transmitter corrupts the encrypted bit stream. For this reason, any system that inserts any bits after encryption and does not extract those bits before they enter into the KG-84A cannot be integrated with the Navy Inmarsat system. The proposed system makes design provisions for the problems arising from using control bits and for this reason is well suited for integration with Inmarsat.

The KG-84A is only capable of processing synchronous bit streams with data rates up to 256 kbps. Because of this limitation, it is wise to consider upgrading to a higher speed crypto device having the same or better features as the KG-84A. The KG-194A, a high speed encryption device already widely used in Navy systems, may be a possible replacement for the KG-84A as the need for higher data rates is pursued [8].

F.   CHAPTER SUMMARY AND CONCLUSION

In this chapter the challenges of implementing a dynamic data rate system were addressed. The first challenge addressed was the method of varying the data rate, where it was determined that the best method of varying the data rate is by varying the modulation level in order to maximize the use of the available bandwidth. For the proposed system, a variable data rate is achieved using variable TCM encoded MQAM. To successfully implement a dynamic data rate system, there needs to be a means for the system to monitor channel conditions. Based upon the measured channel condition, the system decides which level of modulation yields the highest data rate for the prevailing channel conditions. Two techniques were presented in the chapter for monitoring channel conditions. The more effective method of monitoring channel conditions is the RSSI approach because, unlike the error detection approach, the RSSI approach anticipates performance changes and switches the modulation levels before

errors occur. It was explained in this chapter that only the channel between the satellite and ship require monitoring because the links between the satellite and LES have high margins of power. To maximize the capacity of forward and reverse directions of communications, the RSSI approach is applied to monitor channel integrity between the satellite and ship and to determine subsequent modulation levels from the ship and from the LES.

The greatest challenge faced in integrating a dynamic data rate system into Inmarsat is the establishment of efficient protocols for varying data rate. In the proposed system, the symbols to be transmitted are grouped into blocks of symbols. At the beginning of the symbol block, a set of two symbols, transmitted three times for majority voting, informs the demodulator of what level of MQAM to use for demodulating the rest of the data symbols. From the information given by the control symbols, the demodulator can successfully demodulate the rest of the block.

Specific issues require consideration when bits are inserted for control purposes. This is because inserted bits can cause corruption of the encrypted bit stream causing the decryption device to be unable to properly decrypt the message. Fortunately, the design of the proposed system anticipated this problem. Since the control bits are extracted before they enter the decryption device, the bit stream is not corrupted. Furthermore, the delay of the input bit stream to the encryption device and the variable rate of the bit stream entering the crypto device may cause loss of synchronization. Synchronization can be maintained using the KG-84A's external clock feature. Although the KG-84A has features desirable for a dynamic link, it is limited to 256 kbps in synchronous mode. Because of this limitation, it is advisable to replace this crypto equipment with higher speed crypto equipment such as the KG-194A. Doing so will allow the proposed system to take advantage of future satellite upgrades.

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V. CONCLUSION

This thesis investigated the feasibility of integrating a dynamic data rate satellite link for Inmarsat. To provide a meaningful analysis of the system, a functional description of Inmarsat together with its system specifications were given. The system analysis began by conducting a link budget to determine whether the Inmarsat system had link margins in the original static rate design that would allow higher data rates. From the link budget results, it was determined that Inmarsat has considerable margins that, when combined with advance modulation and coding techniques, allows a data rate of 344 kbps for ship-to-satellite communications. On the other hand, the satellite-to-ship link was determined to have a much greater capacity, allowing for a data rate of 688 kbps with the application of forward error correction and coding. The link budget results clearly revealed that Inmarsat was underutilizing the allocated bandwidth and available power. The inefficient use of power and bandwidth makes Inmarsat a prime candidate for the integration of a dynamic data rate link that will optimize the data rate through the channel based upon prevailing channel conditions.

A dynamic data rate satellite link is based on the concept that the channel conditions for communications vary depending upon a variety of variables. A few of the many variables affecting the channel are rain attenuation, polarization mismatch, elevation angle, spot beam coverage, electromagnetic interference (EMI), and the switching between the backup and primary satellites. The varying conditions that affect communications in the channel indicate that different data rates are optimum for different channel properties. To take advantage of the varying channel conditions, a dynamic data rate system that would vary in data rate depending upon the channel's quality and the power available is proposed. To change data rate, the modulation level used for transmission is varied. In instances where the channel condition is favorable, a high level of modulation is used for transmission. In poor channel conditions, a low level of modulation is

used for transmission. Varying the level of modulation takes advantage of the variable conditions of the channel because different levels of modulation require different SNR for successful communication. Higher levels of modulation require more signal power and lower levels of modulation require less signal power. A system model that allows for a dynamic satellite link is given.

Probably the greatest challenge in a dynamic satellite link design is to determine a method of accomplishing successful demodulation. This is because as the modulation type is varied for transmission, the demodulator needs to know the type of modulation used for transmission in order to properly demodulate the received signals. In the system model, the demodulator is informed of the modulation used by the transmitter by means of control bits. The control bits are encoded using the most robust scheme in order to maximize the reliability of determining the constellation size of the received signal. Another challenge in implementing a dynamic satellite link is measurement of the channel's integrity. To measure the channel's integrity, the received signal strength indicator approach is used for the proposed system model. With this approach, the system is able to anticipate varying channel conditions, allowing the transmitter to change modulation type before excessive errors occur at the demodulator.

A.   FUTURE WORK

The studies conducted in this thesis were based on theory. To substantiate the theoretical findings in this thesis, much work is required to verify the feasibility of the proposed system. The first step is to investigate the effects of the non-linear amplifiers on QAM. If it is found that Inmarsat's solid state power amplifiers are non-linear and are unable to support QAM, then this research will need to be reworked with only constant envelope modulations considered. Although the recently launched Inmarsat IV satellites are currently not used for U.S. Navy applications, it would also be beneficial to determine this satellite's amplifier characteristics and its effects on QAM in case the U.S. Navy upgrades to the services provided through the Inmarsat IV satellites. The next

step in determining the feasibility of a dynamic link is to simulate the proposed transceiver's performance through an AWGN channel. Specifically, the threshold values for determining modulation type switching needs to be fully addressed. Recall that the proposed system only monitors the channel between the satellite and the ship to measure the performance of the entire satellite link. However, the satellite-to-ship link has more power available to it than the ship-to-satellite link. Because of this, different thresholds need to be established for the ship-to-LES and LES-to-ship links. Simulations and experiments will allow the determinations of optimum switching thresholds. Furthermore, it is essential to overcome possible latency problems from the proposed link. Note that the control symbol demodulators need to extract the type of modulation before the data symbols can be demodulated. If the data symbols arrive at the demodulator before the control bits are extracted, effective demodulation of the data symbols is not possible.

After simulations confirm the theoretical findings in this thesis, the next logical step is to acquire or design and build the modems and test their performance through experiment. To truly maximize the data rate through the channel, further studies utilizing turbo codes is required. The Shannon limit calculations revealed the theoretical limits; however, the practical limits of using turbo codes with Inmarsat's available bandwidth and power are yet to be presented.

To complete the study, the dynamic link modem needs to be tested with the KG-84A or another approved military encryption device to confirm the encryption device's compatibility with a varying data rate modem. Another U.S. Navy approved encryption device capable of higher data rates is the KG-194. The successful completion of all the above work will allow the successful integration of a dynamic data rate link into Inmarsat.

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APPENDIX

It is unclear whether the *EIRP* values listed in references [2] and [19] are the mobile link *EIRP* or the satellite's total L-band *EIRP*. This thesis makes the assumption that the spot beam *EIRP* (44 dBW) indicated in [2] and [19] is the allocated L-band *EIRP* for each mobile link channel. To substantiate this assumption, first the received E_b / N_o is calculated based on Inmarsat's current specifications. Inmarsat communicates at 128 kbps at a probability of bit error rate of 10^{-7} using QPSK modulation. Based on this information, E_b / N_o is calculated from

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}} \right) \tag{A.1}$$

where P_b is the probability of bit error of a QPSK waveform and E_b / N_o is the average *SNR* per bit [23]. Substituting the minimum P_b maintained by Inmarsat into Equation A.1, E_b / N_o is

$$\frac{E_b}{N_o} = 13.516 = 11.3 \text{ dB} \tag{A.2}$$

where the inverse Q-function is determined using MATLAB's error function as defined in Equations 3.20 and 3.21. Rearranging Equation 3.15 and substituting the value for R, we obtain P_r / N_o to be 62.4 dB.

Rearranging Equation 3.1 and substituting in the values from Table 11 and the P_r / N_o calculated above, we get the *EIRP* for the satellite-to-ship link is calculated as 25.0 dBW. This result only takes into account free space loss. However, it is expected that Inmarsat operates above the minimum P_r / N_o due to margin provisions typical in static data rate designs. Therefore, the actual L-band *EIRP* for Inmarsat mobile link channels is expected to be greater than 25.0 dB. The calculated value of 24.971 dBW is the minimum *EIRP* required for

effective Inmarsat communication if no noise is introduced into the channel and if only free space loss exists. Thus, this value can be treated as a lower bound on $EIRP$. [23]

Considering the minimum $EIRP$ to effectively communicate at 128 kbps at 10^{-7} probability of bit error using QPSK, if the satellite's total L-band $EIRP$ of 44 dBW is shared between two users, we see that the 22 dBW allocated for each user is less than the minimum $EIRP$ of 25.0 dBW. This indicates that two users cannot be supported by Inmarsat. Certainly Inmarsat is able to support more than one user simultaneously. Thus, it is reasonable to assume that the spot beam $EIRP$ indicated in [2] and [19] is the mobile link $EIRP$ and not the satellite's total L-band $EIRP$. [20]

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